Bachelor Thesis

Manoeuvrable Buoy for Offshore Wind Assessment

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Delft University of Technology

TU Delft Delft University of Technology

Challenge the future

BACHELOR THESIS

MANOEUVRABLE BUOY FOR OFFSHORE WIND ASSESSMENT

by

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PREFACE

This design report describes the design of a prototype of an autonomously manoeuvring buoy with a stabilisation platform on top, that provides a stable basis for measurement equipment. This design was commissioned by the Delft University of Technology. The focus of this design report will be on the autonomously manoeuvrability. Two students out of six will be responsible for this part. The other four students of the composed group, will be responsible for the stabilisation platform and a scaled version of a buoy.

In a period of two months, different steps where taken. A background research has been done, a design made, build and tested. All these steps are described in this thesis. With some of these steps, some extra help was offered. Therefore, we would like to thank all the people that were involved or contributed in some way to the project. A special thanks goes out to the following people for their support, advice and commitment to the project:

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SUMMARY

Offshore electrical energy production out of wind energy is a growing market. Wind and water data is needed to measure the most profitable location to set up offshore wind farms. Retrieving the required information can be done by placing expensive masts or deploying moored buoys with measuring equipment. The problem with moored buoys is that they need to be relocated by ship every time wind data from a different position is need, which can be time-consuming and expensive.

The goal of this thesis is to design an autonomous positioning system for a scaled prototype of an offshore wind measurement buoy. The main requirements connected to this goal is that the system must be able to measure its current position, calculate in which direction it must travel to reach its destination and have appropriate propulsion to move the prototype toward that destination. The prototype must also be able to keep its position and prevent itself from drifting off. From tests performed on this prototype, recommendation for the design of a full-scale autonomous positioning buoy are derived.

The system that is designed uses a GPS module to measure its location and a gyroscope to measure its orientation. A microcontroller uses this information to calculate the direction to a pre-programmed destination. This direction is used to sent signals to two motor drivers, which control two DC motors with propellers attached to them. The system is designed in such a way that it can be easily added to the scaled prototype of the buoy: the motors are attached to the underside of the prototype, while the rest is placed inside the prototype.

The different parts of the autonomous positioning system are tested, confirming that they work like they were designed to. The prototype with the system attached can move itself in any horizontal direction, and the correct signals to control the motors are generated. Due to a failing test setup, a test that combines these parts was unsuccessfully.

For the design of the full-scale buoy, a different hull shape for the buoy is recommended. The designed propulsion costs too much power when scaled up to be realizable in full-scale. For more accurate navigation, the use of an electric compass is recommended above a gyroscope. An electric compass measures the Earth's magnetic field to calculated which way is north. Also techniques like Differential GPS or accelerometers can be considered for more accurate positioning. Differential GPS (DGPS) uses signals with GPS corrections sent by land stations to get a more accurate position measurement.

1

INTRODUCTION

1.1. BACKGROUND

The search and exploitation of environment friendly energy sources is an ongoing topic. Fossil energy resources will only last for a limited period of time. Solar energy, wind energy and alternative renewable energy resources are becoming more popular and already play a significant role in the current energy production. In 2013, about 21% of the world's produced electrical energy was renewable energy, while this was 18% in 2003. [1]

Wind energy is one of those renewable energy resources. Especially, the offshore application of wind turbines is a growing market. "The global growth rate of offshore wind energy is 30 percent installed capacity per year." [2] In the future, offshore wind turbines can satisfy a huge part of our energy demands. "In a recent study, the European Environment Agency (EEA) estimates the technical potential of offshore wind energy in the EU to be 30,000 TWh annually. The European Commission estimates total EU electricity demand of between 4,279 TWh and 4,408 TWh in 2030." [3]

Before the placement of wind turbines in an offshore environment, several measurements are required to calculate the profitability of placing those wind turbines. The most interesting factors are the wind speed, its direction and continuity [4] [5]. One technique of measuring this is using a LiDAR(Light Detection And Ranging) [6] device. In essence, LiDAR emits light in the form of a laser, and measures the light that is reflected by the airborne particles, to determine how fast and in which direction those particles are travelling [7]. LiDAR can measure air currents at multiple heights up to 300 meters, making it a very useful tool. For offshore measuring, a LiDAR device is often placed on a buoy. Another way of measuring wind data that is used offshore is using large met masts that are placed on the bottom of the sea. Buoys are preferred, because they are cheaper to deploy, and can be easily relocated by boat.

1.2. GLOBAL PROBLEM DEFINITION

Using a LiDAR device on a buoy poses a problem: A LiDAR needs to be on a completely horizontal platform to perform accurate measurements. Besides that, it would be very convenient to have a buoy that doesn't need to be relocated by boat, because deploying ships to pickup a buoy to place it somewhere else can be expensive and time-consuming. That is possible, when the buoy is designed like some kind of ASV. ASV stands for *Autonomous Surface Vessel* and will be examined in section 1.3.2.

Figure 1.1: LiDAR ZephIR 300

The assignment description [8] refers to an existing buoy as an example to explain the intention. This Seawatch buoy [9] uses a LiDAR module named 'ZephIR 300', shown in figure 1.1. To limit the scope of our thesis,

we use these products as the basis of our design. This is because they both are proven in practise. Together with the two goals mentioned above, the following problem definition is composed:

Designing an actively stabilised platform for the SEAWATCH offshore buoy, to account for measurement errors of the ZephIR 300 LiDAR. Designing autonomous position control for the SEAWATCH buoy. Delivering a working scaled prototype of the buoy with both of these designs.

Figure 1.2: Seawatch buoy

The Seawatch buoy [9] is a wavescan buoy with a LiDAR device on top, shown in figure 1.2. The wavescan buoy is a circular, moored buoy that is equipped with several sensors for obtaining different kinds of meteorological and oceanographical information. This buoy has proven successful for purposes, like collecting data on ocean currents, air and water temperature, wave height and direction and solar radiation. The LiDAR device is affixed to the top of the buoy without any stabilisation. The power required for the measurements can be provided by a battery and by optional solar panels. With this buoy in mind, a navigation system will be designed.

The design of a platform that actively compensates the buoy's tilting angle caused by the waves, can be found in the bachelor theses [10] [11] of the four other participants of the project group. The second issue is the repositioning of the buoy. The goal is to design a system that makes a buoy able to travel to a given position autonomously. With this in mind, the search begins to find the situation with regard to the current developments in this area.

1.3. STATE-OF-THE-ART ANALYSIS

Before formulating the exact requirements of the design, an analysis of the existing technologies in the field of the subject is conducted. In this analysis, the subject is split up into two parts: On one hand a buoy that does wind measurements using a LiDAR device and on the other hand the technology that enables the buoy to navigate to a given position autonomously.

1.3.1. LIDAR BUOY

There are multiple different kinds of buoys both available on the market and under development that use LiDAR technology for wind measurement. The most interesting ones will be further examined and compared.

The Flidar (Floating LiDAR) buoy [12] is a moored buoy that is large compared to the Seawatch buoy (4 meter diameter versus 2.8 meter). This buoy, shown in figure 1.3a, is more specifically designed for wind measurements. The buoy cannot do as many different oceanographic and meteorologic measurements as the Seawatch buoy, but is limited to measuring air pressure, humidity and temperature in addition to the LiDAR measurements. The Flidar uses a passive stabilisation of the LiDAR device for more accurate measurements. The larger platform and weight makes the buoy more stable in the water, but also make it more troublesome to reposition the buoy, since a larger ship with a larger crane is required to lift it out of the water. The larger platform does make the usage of small wind turbines on the Flidar buoy possible in addition to solar panels, increasing the time the buoy can do measurements without running out of power.

The AXYS WindSentinel [13] from figure 1.3b is another existing moored buoy platform modified to do wind measurement. The AXYS NOMAD buoy platform, on which the WindSentinel is based, is shaped more like the hull of a ship, than like a circular buoy. This hull shape helps preventing the buoy from turning around its vertical axis. This increases the accuracy of wind direction measurements. The shape also makes dragging the buoy to a new location easier. The buoy does not have sensors for other measurements, and the LiDAR device is not stabilized. The on board power is supplied by solar panels, small wind turbines and a fuel cell.

While the previously mentioned buoys are commercially available, the Neptune Project [14] buoy is still under development. A render is shown in figure 1.3c. This moored buoy does not consist of a single large

floating body, but it has four smaller floats connected in a square configuration. On top of these floaters, the LiDAR device is secure on an actively stabilized platform. The buoy has in addition to the LiDAR device a sensor for measuring ocean waves. The on board power is generated by small wind turbines and solar panels.

(a) Flidar

(b) AXYS WindSentinel

(c) Neptune buoy

Figure 1.3: Different LiDAR Buoys

Each existing Lidar buoy mentioned above is equipped with a Global Positioning System (GPS) receiver to measure its current position. The position of the buoy is used to correct the wind measurement data with the drifting of the buoy around its anchor point. The buoys that have wave measurement equipment can also correct the measured wind data with the angular displacement of the buoy. These corrections are done with signal processing software specially designed for this purpose. Furthermore, all buoys described above have ways of short range and satellite communication to send the measurements back to the main land in regular intervals.

The different types of LiDAR buoys, including the seawatch buoy, and their properties, are summarised in table 1.1. An important observation that can be made from this table is that none of the buoys can move itself autonomously, and only one uses active stabilisation. Besides that, all systems (of which the buoys are a part) use software data correction to make their measured data more accurate.

Property	SeaWatch	Flidar	Wind Sentinel	Neptune Project
Available on the market	x	x	x	
Active platform stabilisation				x
Passive platform stabilisation		x		
Software data correction	x	x	x	x
Wave measurement	x			x
GPS Receiver	x		x	x
Short range communication	GSM/GPRS & VHF/UHF radio	GPRS/modem Dial-up & Wifi	GPRS & 3G	information not released
Satellite Communication	x	x	x	x
Moored Buoy	x	x	x	x
Autonomous Positioning				
PV Cells	(Optional)	x	x	x
Wind Turbines		x	x	x
Fuel Cells			x	

Table 1.1: Existing LiDAR Buoys with their properties

1.3.2. AUTONOMOUS NAVIGATION

Autonomous navigation on the ocean is not done by buoys. Unmanned vessels on the water surface only exist in the form of small boats. A collective name for all boats and buoys that navigate without a person driving it on board, is Autonomous Surface Vessel (ASV). ASVs are used in the military, commercial and research sectors for a wide range of purposes, which include [15]:

- Military and security purposes such as mine field exploration, weapon testing, ocean surveillance and marine personnel training.
- Environmental monitoring and underwater positioning for commercial uses, such as on off-shore oil and/or gas sites.
- Gathering of information on seawater and wind on the ocean's surface for scientific purposes.

Figure 1.4: ASV Ltd C-Enduro

One of the commercially available ASVs on the market today is the C-Enduro made by the company 'ASV Ltd' [16]. The C-Enduro, shown in figure 1.4, is a long endurance autonomous vessel that can be equipped with different kinds of sensors for monitoring for example the CO_2 rates, solar and wind or ocean waves and currents on the surface. This particular vessel has the shape of a flat catamaran and is 4.2 m long and 2.4 m wide. The large flat top surface of the vessel is covered almost entirely in solar panels, and it is equipped with a wind turbine as wide as its hull. Using these power sources in addition to a small diesel generator, the vessel can cover more than 6000 km during the three months it can be at sea at a time. It uses satellite communication and GPS for it positioning.

A schematic representation of the navigation system in an ASV, that is used to measure nutrients and fluorescence in seawater, is shown in figure 1.5 [17]. The ASV has a central processing unit (CPU) that gets the position and direction of the buoy from a GPS receiver and electric compass, and uses this information to send the right amount of power to the thrusters to move the vessel to its destination. The vessel in question does not have a rudder and is therefore steered by the difference in thrust which the thrusters on both sides of the vessel produce. The CPU of the vessel also receives DGPS signals via telephone communication and sends that to the GPS unit. A DGPS signal contains GPS information of a land station and is used to correct the GPS receiver and make it more accurate. The CPU also sends the position of the vessel back to land via satellite communication. Using DGPS, the position can be calculated with an accuracy of 2 m.
What the CPU of this vessel does exactly, is not described in the paper. What is described, is that the system has two modes: one mode that is active when the vessel is far away from its target. In this mode the vessel only determines its position in intervals of 140 seconds. The course is also adjusted only once per interval. This conserves the energy consumption of the CPU and the GPS unit. The other mode is active when the vessel is closer than 600 m near its target. In this mode, the course is modified more often to reach the destination accurately.

1.4. OUTLINE OF THE THESIS

Having described the existing techniques in the field of the subject, the designing of a navigating LiDAR buoy is described in the rest of this thesis, divided into the following chapters: The next chapter, chapter 2, holds the objective of this thesis, the requirements of the design and the scope of the project. Chapter 3 discusses the choices and actions made during the design of the prototype. Chapter 4 presents the method of testing of the prototype and the results of those tests. The conclusions we draw from the tests are discussed in chapter 5, and chapter 6 contains the recommendations about the project.

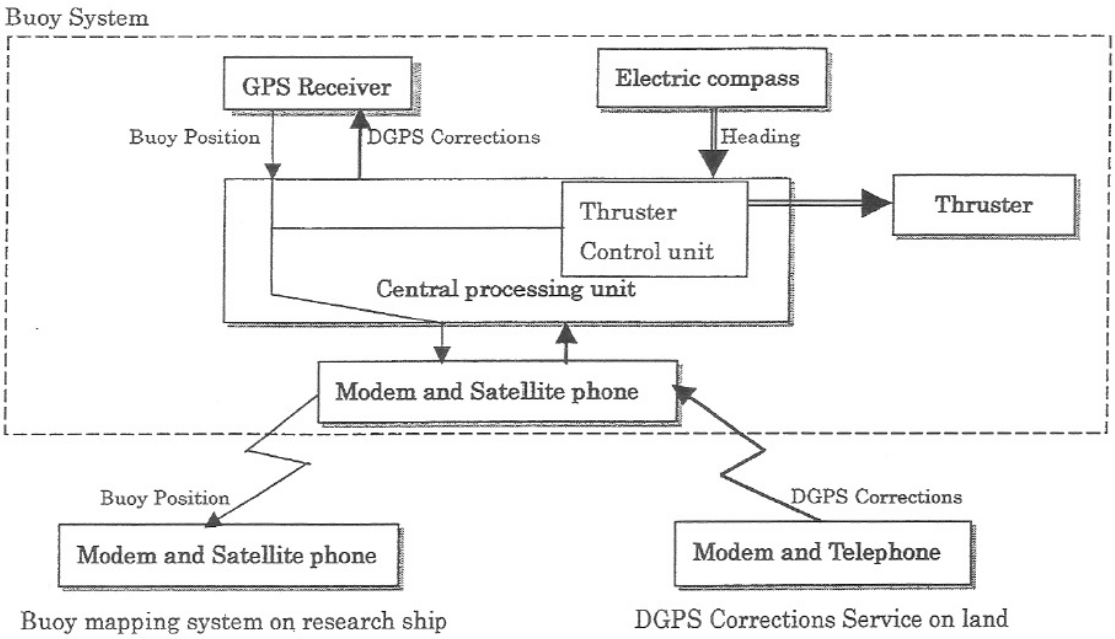


Figure 1.5: Schematic representation of a navigation system of an autonomous surface vessel

2

PROBLEM DEFINITION

The problem needs to be specified in a more detailed way, before a fitting solution can be designed. That is why a list of requirements are set to specify a desirable performance for the prototype and the full-scaled buoy. These requirements are set in section 2.1.1. In section 2.1.2 is described how the prototype requirements are converted to requirements for the full-scaled buoy. The remaining requirements concerning surrounding topics, are added in sections 2.1.3 to 2.1.5.

2.1. REQUIREMENTS

For setting the right requirement, it is necessary to focus on the global problem definition, which is set in section 1.2. That is why it is repeated below. Besides that, communication with the other participants of the project group must ensure that no conflicting requirements are set.

Designing an actively stabilised platform for the SEAWATCH offshore buoy, to account for measurement errors of the ZephIR 300 LiDAR. Designing autonomous position control for the SEAWATCH buoy. Delivering a working scaled prototype of the buoy with both of these designs.

2.1.1. PROTOTYPE REQUIREMENTS

In consultation with the other participants of the project group, common design requirements are set regarding the scale of the prototype. For the group working on the stabilisation, the dimensions of the prototype cannot be too small, since some parts of the prototype, like the linear actuators, are not available at a too small size. Making the dimensions too big, will result in larger production costs and an unmanageable prototype. The following scale is selected:

2.1.1 *For the prototype, a scale of 1:5 is held in relation to the full-scaled buoy.*

The start date is the 22th of April 2014 and the deadline of this report is the 18th of June 2014. The prototype needs to be build by then, and test must be performed. Therefore, the following requirement can be set:

2.1.2 *The prototype is built in a time span of 2 months.*

For this project, a budget was allocated. To determine the size of the budget, a estimation was done. This estimation can be found in appendix A. This includes the budget for all three subgroups.

2.1.3 *The prototype does not exceed the budget of 820 euros.*

The buoy must be able to operate while drifting in turbulent waters. From this, a number requirements can be derived.

2.1.4 *All buoy components that will be submerged when the buoy is in the water, need to be completely watertight.*

2.1.5 *All components above the surface when the buoy is in the water, need to be at least splash waterproof. This means that the electronics aboard the prototype may not come in contact with any water when water is splashed against it.*

For the total weight of the buoy, the navigation system can not add too much weight to the buoy, because it increases risk of sinking. The prototype is able to keep afloat if its draft increases somewhat. A draft increase of 10% should be acceptable, so an estimation of a reasonable weight comes out to a maximum of 10% of the total allowed weight. Since the prototype has an 1:5 scale, the weight needs to be scaled with a factor 5^3, one time in each dimension. Since the full-scaled buoy has a weight of approximately 1200 kg [9], the following requirement can be set:

2.1.6 *The navigation system mass may not exceed a total of 1 kg.*

The global problem definition, repeated in section 2.1, implies that the prototype needs to able to relocated itself to a given position, and needs to prevent drifting off. At first, a top speed is argued and defined. Besides that, the minimum accuracy of the position is set.

The speed of the prototype is obtained by first setting a desired speed for the full-scale buoy. A speed of at least 5 km/h (1.4 m/s) is desirable for the real buoy, because with such a speed the buoy will be able to move around the area where a new wind farm is planned in a manner of hours (since wind farms have a typical surface area of 10 to 30 km^2). Besides that, the speed of currents at sea, for example the North Sea and the Norwegian Sea, rarely exceeds 5 km/h (1.4 m/s) [18], which implies that the buoy is almost always capable of dealing with current. Scaling down this desired top speed for the buoy to a desired top speed for the prototype is done using the Froude number. The Froude number is a dimensionless value used to describe certain flow characteristics. It could be described as the ratio of the inertia of a ship to the gravitational forces working on it. In this case, the Froude number is used to describe the amount of drag resistance the buoy has in the water, and it can be calculated with equation 2.1. By giving the prototype the same Froude number as the full-scaled buoy, the amount of drag resistance the prototype has at its top speed is comparable to the amount of drag resistance of the full-scale buoy. Using equation 2.1, a desired top speed of 2 km/s (0.56 msecond) is obtained.

$$Fd = \frac{v}{\sqrt{gL}} \tag{2.1}$$

2.1.7 *The prototype sails at a minimum top speed of 0.62 m/s.*

2.1.8 *The prototype obtains its current position from a positioning system that has an average deviation of at most 10 m.*

For the navigation of the buoy to its navigation, a number of requirements can be set. For the requirement below, it must be noted that the buoy is only capable of maneuvering in waters with a sufficient depth and a limited current.

2.1.9 *The prototype calculates the direction to its destination, and is able to make it there (as long as the destination is reachable in one line).*

2.1.10 *The prototype reaches its destination with a maximum deviation as small as its positioning system allows.*

2.1.11 *The prototype keeps its position with a maximum deviation as small as its positioning system allows.*

For future purposes, the buoy gets an override function. This way, the buoy may be extended with a manual manoeuvre control. An other purpose can be the correction of the yaw using the propulsion system. In figure 2.1, different movements like yaw are illustrated.

2.1.12 *The navigation system has an override function that allows another system or a user to control the propulsion of the buoy.*

2.1.13 *The propellers of the buoy are placed in such a way that the buoy can rotate around its Z-axis, to compensate the yaw, without drifting away.*

2.1.14 *The autonomous positioning system is placed on the buoy in such a way that it does not jeopardize the stability of the buoy.*

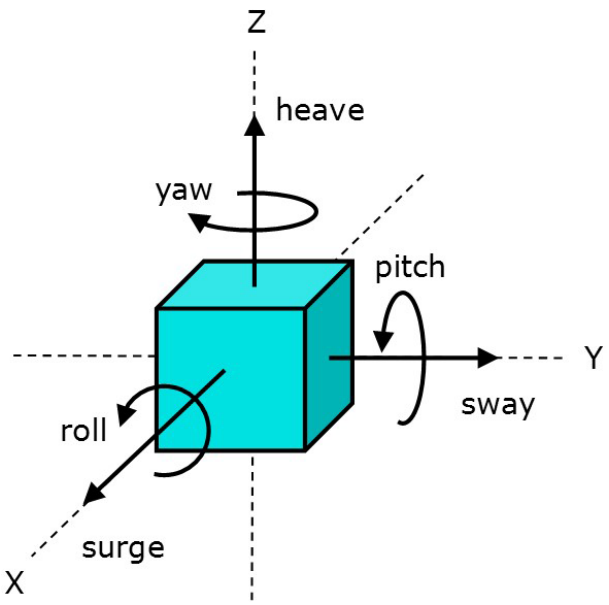


Figure 2.1: six degrees of freedom

2.1.2. FULL-SCALED BUOY REQUIREMENTS

Some of the requirements set for the prototype apply to the full-scaled buoy as well, while others are not relevant to the full-scaled buoy. Table 2.1 shows what requirements of the prototype can be applied to the full-scaled design, and what requirements need to be modified before they can be applied. Some of these modifications are explained as follows:

- Since the full-scale buoy is 5 times bigger than the prototype, the volume and weight of components like the motors and propellers are approximately 125 times larger because of the three dimensions.
- For the precision of reaching its destination and of staying on one location, the buoy is dependent on the accuracy of the GPS unit aboard. Since the accuracy of GPS is 7.8 m on average, the deviation the buoy can have from its intended position is at least as large as that.

Requirement	Applicable on full-scaled buoy?	Required modifications
Requirement 2.1.1	No	
Requirement 2.1.2	No	
Requirement 2.1.3	No	
Requirement 2.1.4	Yes	None
Requirement 2.1.5	Yes	All components need to be fully watertight.
Requirement 2.1.6	Yes	Maximum weight approximately 125 times larger.
Requirement 2.1.7	Yes	Sailing speed scaled to approximately 1.4 m/s
Requirement 2.1.8	Yes	None
Requirement 2.1.9	Yes	None
Requirement 2.1.10	Yes	None
Requirement 2.1.11	Yes	None
Requirement 2.1.12	Yes	None
Requirement 2.1.13	Yes	None
Requirement 2.1.14	Yes	None

Table 2.1: Translation of prototype requirements to full-scaled buoy.

Besides these requirements, there are some requirements that are only of interest to the full-scaled buoy. One of those is the time the buoy has to be able to be on the sea autonomously. Because wind measurement are often not a snapshot, but an observation over longer periods of time, the following requirement is set:

2.1.15 *The buoy must be able to be at sea autonomously for at least a month.*

This requirement results in the need for strict energy management. The Seawatch buoy has a lithium battery bank of 9792 Ah and a lead-acid battery bank of 248 Ah at 12 V. These battery banks are fully charged at deployment and can be recharged using the PV cells on the Seawtach buoy. These cells can provide a total of 180 W of electrical power [9]. The Seawatch buoy will be outfitted with extra equipment of active stabilisation and autonomous positioning, and it needs to be close to self sufficient in its energy consumption. Therefore the capacity of the battery banks that will be used on the full-scaled buoy, is doubled. Via equation 2.2 the total power the buoy has at its disposal is roughly 400 W. The existing systems of the buoy consume around 200 W [19]. The remaining available 200 W is divided as follows: the active compensation can't use more than 75 W and the autonomous position control can't use more than 125 W.

$$Power = \frac{(2 \times (I_{\text{leadacid}} + I_{\text{lithium}}) \times U) + S \times h \times \eta}{h} = 395W \tag{2.2}$$

with:

- I_{leadacid} = 9792 Ah
- I_{lithium} = 248 Ah
- U = 12 V
- S = 180 W
- h = 720 hours/month
- η = 1/3 [Fraction of time the solar panel is operational]

This results in the following requirement:

2.1.16 *The energy consumption of the navigation and propulsion units may not exceed 125* W.

2.1.3. PRODUCTION REQUIREMENTS

Should the buoy ever be taken into production, the following requirements are set for the production of the buoys:

The environment friendly image made by providing techniques for wind farms, will be reinforced by ordering components or raw materials at companies that have the same reputation, or at least not a bad reputation.

2.1.17 *Components and raw materials are bought at shops or from companies with a non-controversial image.*

During its lifetime the buoy is handled by multiple people, both during its production and during it deployment to and recollection from sea. These interactions must not be dangerous for anyone who is involved. For example the propellers of the buoy may never be turning when the buoy is being hauled aboard, because they might injure someone. Therefore, a reasonable safety margin must be respected.

2.1.18 *The production and deployment of the buoy happens following the safety regulations of that sector, for example the regulations for use of international waters [20].*

On the end of its life-time, the buoy still should not be harmful to the environment. Therefore, another requirement with respect to its materials is set about recyclability. The materials used on the buoy that will be recyclable will be most likely the metals and the high quality synthetics that are used.

2.1.19 *At least 70% of the buoy is recyclable.*

2.1.4. ECOLOGICAL REQUIREMENTS

The full-scale buoy will be deployed in the ecological offshore environment, so it must not harm that environment. Therefore, the following requirement is set:

2.1.20 *The buoy does not contaminate the environment in which it is deployed. When malfunctioning, the ecological effect must not exceed the limits set by (European) regulations.*

2.1.21 *The buoy and its components are produced following the (European) ecological regulations regarding the production of technology.*

2.1.5. BUSINESS REQUIREMENTS

From the perspective of the market, the navigation component of the product must be as compatible as possible, without losing any of its functionality. The next requirement can be set:

2.1.22 *The navigation system needs to be compatible with as many existing buoys as possible.*

2.2. SCOPE

It is not realistic to take all prototype and full sized buoy requirements into account, due to limited time available for the design process. Therefore, a few compromises are made regarding the requirements of the prototype. The compromises made are listed below:

- A regular buoy, such as the Seawatch buoy, is not designed for manoeuvring, making sailing with it not very efficient. However, a different hull shape for the prototype will not be designed in this thesis. Instead, the hull shape of a Seawatch buoy will be used as starting point. This decision is made, because a buoy shaped hull is more stable on the waves. Stabilising the platform is easier when the prototype itself is more stable. This stabilizing platform has priority above making it move more efficiently during this project. To make sure that the stabilizing platform works on board of a buoy, the prototype needs to have a buoy shape.
- For the energy management, only rough calculations are done for the full-scaled buoy. For the prototype, power consumption is not taken into account as a requirement.
- A power supply for the prototype is not designed in this thesis. Instead, a PC power supply with a 12 V and a 5 V connection is used to power the prototype.
- From the six degrees of freedom, only the surge and the sway, explained in figure 2.1, are controlled by the navigation system. The option to control the yaw will be kept open.

3

DESIGN PROCESS

The system to be designed will consist of the following parts:

- The controller, which is the central element of the system;
- The positioning system, which obtains its position and passes it to the controller;
- The propulsion, which enables the buoy to relocate;
- The motor driver, which uses the signals of the controller to supply the motors with the right voltage;
- The software on the controller, required to make the parts work as one system and to calculate the route.

In following sections, the choices and considerations made to design these components are discussed.

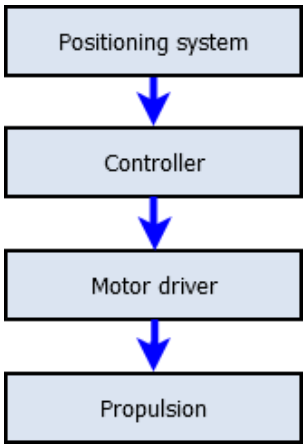


Figure 3.1: Overview diagram

3.1. CONTROLLER

To control the whole autonomous position control system, a central controlling and computing unit is needed. There are several options to fill this place. Two options are taken into consideration: a Field Programmable Gate Array (FPGA) chip and a microcontroller. A FPGA needs to be programmed using VHDL, a hardware description language, while a microcontroller can be programmed in C. C is used much more widely for embedded programming and hence libraries for many functions are commonly available. Therefore, programming in it will be preferable. Microcontrollers also have built-in protocols for for example UART communication (which will be usefull for communicating with sensors and such), while on an FPGA those protocols need to be implemented from the bottom up. This is why a microcontroller is selected for the prototype.

There are two kinds of microcontroller boards that can be provided by the Delft University of Technology to use during this project. One board uses a Atmel ATmega8 microcontroller [21] while the other uses a LPC1343 microcontroller [22]. Some relevant features of both microcontrollers are shown in table 3.1. I^2C is a communication protocol that can be used to communicate with multiple devices on the same bus. Communication with sensors like the gyroscopes discussed in section 3.2 is done with I^2C, which is why a microcontroller with this function is preferred. Based on the features listed in the table, the LPC1343 is the more suitable microcontroller of the two. Buying another board with a microcontroller with even better specifications is an option, but since the available microcontroller is already sufficient for our purpose, there was no need to buy an other microcontroller.

The available board that uses this microcontroller, the Olimex LPC-P1343 board (for more information about his board, see appendix D), has a limited number of available Input/Output pins, since some of the pins of the microcontroller are used for the USB connection, buttons, LEDs, the I^2C and UART connections

of the board. The number of remaining pins is expected to be sufficient for the prototype and that is why the LPC-P1343 microcontroller board is selected. However the amount of pins that will be needed for the complete design could not be counted yet at this stage of the design.

The LPC-1343 microcontroller is not perfect, however. It has no hardware to perform floating point operations. This is a limitation that needs to be taken into consideration while designing the algorithm for calculating the direction of the buoy, in section 3.5. The solution to this limitation will be using fixed point operations to approximate the answers. The fact that the number of Input/Output pins is limited also needs to be taken into consideration during the rest of the design.

	ATmega8	LPC1343
Clock speed	16 MHz	72 MHz
CPU	8 bit	32 bit
SRAM memory	1 kB	8 kB
Flash memory	8 kB	32 kB
In/Out pins	23	42
UART connections	1	1
I^2C connections	0	1

Table 3.1: Comparison of the ATmega8 and LPC1343 microcontrollers

3.2. POSITIONING SYSTEM

The prototype need to be able to obtain its position from some kind of sensor. The full-scale buoy obtains its position from GPS signals. To increase the scalability of the program running on the microcontroller, GPS would be a smart choice. While other positioning systems would use different protocols to send their data, a GPS that is placed on the prototype will send data in the same way a GPS module on the life-sized buoy would. Another reason is that a GPS module is relatively small, which makes it easy to fit on the buoy, and that it does not require aditional equipment to be placed away from the prototype. A disadvantage in relation to other positioning systems, e.g. an acoustic positioning system, is that a regular GPS module has a poor indoor performance.

To communicate its data to a user, in this case the microcontroller, the GPS module needs to have a suitable communication protocol at its disposal. Since the microcontroller has a serial UART [24] connection available, this way of serial communication is preferred. The size, price and compatibility with the system were taken into consideration for the choice for the 'Navilock NL-552ETTL GPS receiver'. More information about thid GPS module can be found in appendix C. It is in size better than alternatives, which are so small that they cannot be soldered into a system easily, like the 'A2200A GPS Module', while still being affordable. But most importantly, it communicates in a way that the microcontroller can easily use: it sends bytes using a Universal Asynchronous Receiver/Transmitter (UART) with a baud rate of 38400. The microcontroller has, as mentioned in section 3.1 a built-in UART component. The information sent by the chosen GPS module, is represented in the NMEA-0183 protocol. This protocol uses sentences formed by comma-separated words. This kind of sentences can easily be interpreted by the microcontroller. The NMEA-0183 protocol is the standard for communicating positioning information for naval applications.

The GPS can also provide the buoy with data on its speed and direction, but this data is only reliable when the GPS receiver is moving at a high enough speed. Since the buoy, and especially the prototype, is not going to be moving that fast, a different way of measuring the orientation of the buoy is required. To implement the stabilized platform, the prototype will be equipped with gyroscopes that measure its rotational speed around all three axis. By taking the integral of the rotational speed around the z-axis, the orientation of the buoy can be obtained. This implementation is noise and distortion sensitive, since the noise and distortion will be integrated, but despite that, this method is chosen to measure the orientation of the buoy. The distortion on the signal is caused by an average rotational speed that the gyroscope measures while it is completely stationary. The distortion problem is tackled by calibrating the gyroscope. By taking hundreds of samples in a fixed position, the average distortion is calculated and subtracted from the output signal of the sensor. The main advantage of using the used gyroscope, is that no additional sensors are needed. This means that no

additional ports of the microcontroller are required to connect that sensor and no separate code has to be written to communicate with that sensor.

The gyroscope sensors chosen are of the type Parallax L3G4200D. This type of sensor can measure rotation speeds of up to 250 degrees/second with an accuracy of 8.75 millidegree per second/degree [26].

3.3. PROPULSION DESIGN

The buoy needs a way to move itself towards its destination. In this section the method of propulsion is chosen, the specifications of this propulsion are considered and the components are selected that meet the specifications.

The propulsion of a large majority of all ships on the sea are realised with propellers outside the hull, but there are other methods of propulsion such as sails and pump-jets. Sails are not a usable option for the buoy, because they rely on the wind for their power, so the speed of the buoy would be unreliable at best. Pump-jets use propellers inside the hull to pump water in and expel it through a nuzzle at high speeds. Pump-jets provide high speed and manoeuvrability for boats, but they are less efficient at lower speeds and more expensive to install than regular propellers. This is why motors with propellers outside of the hull are selected as the method for propulsion.

3.3.1. THE MOTORS

A choice must be made between different types of electric motors: AC motors, brushed DC motors and brushless DC motors. For this choice, both technical aspects such as power and efficiency and economical aspects such as costs, need to be considered. Firstly, the buoy has a battery as a DC voltage source. This is why only DC motors are considered. There are two main types of DC motors: brushed and brushless motors.

Brushed motors have in general a lower efficiency than brushless motors, because the brushes cause friction. The brushes wear out and need to be replaced periodically, causing maintenance costs. Brushed motors can, however, be controlled more easily, since they require just two control wires, with no specifications to the timing of the control signals, instead of a three phase control signal with timing that determines its rotational speed. Besides that, brushed motors are far cheaper to buy than brushless motors. For these reasons, the choice for brushed motors is made for the prototype.

The required power and rotational speed of the motors of the prototype is chosen by comparing the dimensions and specifications of the prototype to a model boat. The model boat selected to be compared is a model of the ship M. V. Ballyloran [27]. This boat has a weight of 16.4 kg and uses a 12 V Marx Decaperm motor with a gear ratio of 1:2.75. This motor produces a power of 42 W at maximum efficiency and rotates at a speed of 8400 rotations per minute (rpm). Because of the gearbox, the rotation speed of the propeller of the model boat is approximately 3050 rpm. The prototype of the buoy is expected to weigh about 10 kg, somewhat less than the model boat. The width of the boat is 216 mm, while the prototype has a width of 526 mm, and while the model boat has a streamlined V-shaped hull, the prototype has a less streamlined round hull. This means the water resistance of the buoy is a lot higher than that of the model ship. Although the exact top speed of the model boat is not mentioned in the source, it is very likely that the model boat has a higher top speed than the desired 2 km/h of the prototype. The exact weight of the prototype and its friction in the water were still unknown while choosing the motors, but since the example model boat has both a higher weight and higher top speed, 42 W is assumed to be enough power to propel the prototype.

Waterproof motors are not very easy to find. but it still is an option to buy an waterproof motor. Most motors for model boats use a propeller shaft through the rear bottom of the boat, but that concept is unusable for a buoy purpose. The costs of a waterproof motor are a lot higher than a regular motor. Given the fact that there is a limited budget, the choice is made to accept the challenge of waterproofing it by hand. The designing of a waterproof housing, is described in section 3.3.5.

3.3.2. THE PROPELLERS

The pitch and diameter are the most important dimensions of the propeller of a boat. The pitch of a propeller is the length the propeller would move forward if it were to do one complete turn in a solid substance.

The pitch is related to the rotational speed of a propeller and the speed of the boat via equation 3.1. In this equation, p is the pitch of the propeller in m, v is the speed of the buoy in m/s, ω is the rotational speed of the motor in rad/s and S the slip of the propeller. The value $(1-S)$ represents how much of the pitch length the vessel actually moves through water, when the propellers move one complete turn. The slip is a unitless value, and in case of a regular model ship hull, this value is approximately 0.30, for the prototype the slip is expected to be higher, but could not be measured before choosing the propellers and motors. Using equation 3.1 with 2 km/h desired top speed, 3000 rpm rotational speed and a slip of 0.50, a desired pitch of 22 mm is obtained.

$$p = \frac{2\pi v}{\omega(1-S)} \tag{3.1}$$

The diameter of the propeller is chosen in the same way the required power and rotational speed for the motors was: by looking at examples of model boats. The model of the ship M. V. Ballyloran [27] uses a propeller of 42 mm in diameter. Because the propeller size is often chosen by relating it to the power of the motor, a propeller size of 42 mm is assumed to be sufficient for the prototype.

3.3.3. PLACEMENT OF THE PROPULSION

There are different choices concerning the number of motors and propellers and the orientation in which they are mounted on the buoy. The first possibility is using one or more propellers with a rudder(s) behind it. This option provides good navigational precision when moving to a new location, but compensating the yaw is more difficult for the buoy when a rudder would be used, because the buoy need to move away from its position for the rudder to be effective. Rudders are most effective when the vessel they are attached to, has a reasonable speed. Since the prototype is not very fast, a rudder will most likely not be the most optimal solution. Also, choosing or designing a rudder suitable for the buoy is another design step that is not strictly necessary, which would only cost extra time. This is why a rudder is not preferred in this case.

Another option is mounting two motors with propeller on a different place on the buoy. A configurations with 3 or more motors do not provide much more controllability, and extra cost for the third motor is not worth it. With only two motors, there are many possible configurations. The two configurations shown in figure 3.2 are considered in particular. This is because the two configurations are well suited to compensate for a certain aspect of the drifting of the buoy: Configuration 1 compensates the yaw especially well, while configuration 2 is very suitable for the compensation of surge and sway. However, surge and sway can be compensated with configuration 1 while configuration 2 has no way of compensating for the yaw. When moving to a new location, both motors need to be turning at full speed for the highest top speed. In this case, the motors in the configuration 2 work partially against each other. Other configurations are not more efficient or do not provide more controllability than configuration 1. This is why the configuration 1 is chosen for the prototype.

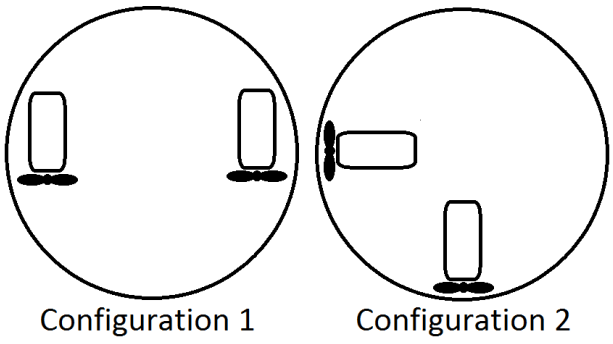


Figure 3.2: Schematic view of the two considered motor placement configurations.

The choice is made for the prototype to attach the propellers to the motors with shaft that is as short as possible, like visualised in figure 3.2. This way, the motors can be mounted on the underside of the buoy. The choice for this placement of the motors is made because it is a solution that is uncomplicated: it does not require a shaft to go through the hull of the prototype, and requires no joints or gears to connect the motor and propellers to that shaft. Another point in favor of this solution is that it increases the modularity of the

solution: it can be mounted on different vessel without having to integrate the motor and motor shaft into that vessel.

3.3.4. SELECTED COMPONENTS

For the prototype, two motors of the type Como Drill 919D with a 2.5:1 gearbox are chosen. More information on this motor can be found in appendix E. Together, the motors have a power rating of 42.4 W (21.2 W each), and they have a rotational speed of 5000 rpm at maximum efficiency at 12V DC. The motors provide the desired power, although their rotational speed is higher than the value mentioned in section 3.3. The speed of the motor can be easily scaled down using the motor driver (see section 3.4), so having a higher maximum rotational speed is not undesirable. The motors are equipped with a capacitor of 0.22 μF parallel across its terminals. This is to make sure that when the current through the motor is suddenly cut off, the inductor current does not cause a very high voltage across the connections of the motor for a short period of time.

The propellers selected have a diameter of 50 mm and a pitch of 26 mm. The propellers are larger both in size and pitch than the values mentioned above. This is to account for the possibility that the slip of the prototype is higher than the 0.50 assumed while calculating the pitch. A larger propeller can provide more forward force per rotation, which makes these propellers useful when operating the motors below their maximum rotational speed.

The propulsion requirements for the full-scale buoy can be obtained by scaling up the properties of the motors and propellers of the prototype. The scale factor of the power of a motor is typically the scale factor squared, making the total power consumed by the large-scale buoy, if these motors are scaled up, 1040 W, which would exceed the set 125 W limit. The size of the propellers, when scaled up, will be 25 cm. However, at this stage of the design process no conclusion can be drawn as to whether the selected motors and propellers are sufficient for the prototype. The requirements for the motors and propellers are discussed in the recommendations (chapter 6).

3.3.5. WATERPROOFING

The main disadvantage of mounting the motors on the underside of the prototype is that the motors need to be in a small enclosure that needs to be entirely watertight, with the rotating motor shaft coming out of it. Figure 3.3 shows the parts of the designed solution. As watertight capsule, a 50 mm diameter PVC drain pipe (1) with two tightly fitting caps (2 and 8) on both ends is used. This pipe can be easily attached to the underside of the buoy using PVC fixing clips (shown in the figure 1). Two PVC rings (3 and 5) hold the motor (4) in place, and the motor shaft exits the capsule through a rubber ring (7), that is fitted into the cap (8). The motor shaft (6) is designed to connect the 6 mm rotation shaft of the motor to the 3.3 mm screw-thread shaft on which the propeller (9) can be fastened. This motor shaft has a section between the motor and the propeller where it has a smooth surface: this part is were it leaves the capsule through the rubber ring. The wires of the motor leave the capsule though the other end (2). A hole is made in the cap just large enough for the wires, and after they are pulled through that gap, the wires are glued into place. To prevent the water from dripping in slowly through the rubber ring when the motor shaft is rotating, some petroleum jelly is applied between the shaft and the ring. This also reduces the friction of the shaft caused by the rubber ring. The last step of the waterproofing, is adding a 5.0 A fuse to the motor circuit. If there occurs a leakage, the resulting short circuit will only blow the fuse.

3.4. MOTOR DRIVER

The motors can be powered by a DC voltage signal of between 4.5 and 15 V. The microcontroller that will be used to do the navigation calculations can only supply low power 3.3 V signals, however. An option is to control the motor speed by modifying the magnitude of the voltage across the connections of the motor. But controlling the magnitude of a voltage with the microcontroller requires a digital-analog converter that needs to be able to provide enough power for the motors to run at full speed. This is an expensive part to buy, or a time-consuming part to build. This is why, to control the speed of the motor, Pulse Width Modulation (PWM) is used by the microcontroller. PWM is a technique that switches a DC source on and off with a constant frequency and an adjustable duty cycle to regulate the amount of power supplied to the load. Using PWM maintains a large part of the torque produced at DC input, while decreasing the rotation speed. The frequency of the PWM signal to be sent to the motors is chosen to be 500 Hz. This frequency is high enough

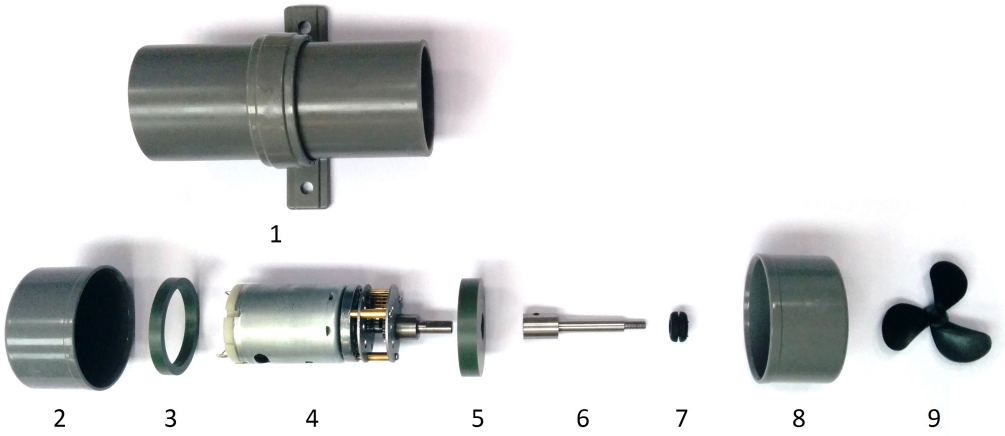


Figure 3.3: Parts of the designed waterproof casing.

to minimize the stutter that occurs when the motor is switched on and off with a frequency that is too low. On the other hand, 500 Hz is low enough for the effects of the capacitor parallel to the motor to be small: at high frequencies, the impedance of the capacitor becomes low, meaning that a large part of current flows through the capacitor instead of the motor.

The original PWM signal is a 3.3 V signal produced by the microcontroller. This 3.3 V PWM signal needs to be converted to a 12 V signal for the motors. This is achieved by switching a 12 V source on and off with using the 3.3 V PWM signal from the microcontroller. In figure 3.4, the implementation is shown with a NMOS transistor. In this configuration, the NMOS transistor is connected to ground and has a job to pull down the voltage at the negative terminal of the motor, while the positive terminal is connected with 12 V DC.

The motor is now able to turn in one direction. To make the motor spin in both directions, the polarity on the motors needs to be reversed. Therefore, a half bridge (H-bridge) is used. A H-bridge is a system of switching transistors used to reverse the voltage across two terminals. The H-bridge that is used has two input signals. When one of those inputs is 1 and the other 0, the voltage across the load becomes positive, while when the inputs are inverted, the voltage across the load is reversed and becomes negative. In figure 3.4, the implementation of the H-bridge is shown. Two such circuits are used in the propulsion system: one for each motor.

The H-bridges that were selected to be used in the motor driver are of the type L298N, produced by STMicroelectronics [28]. These H-bridges can operate with input voltages between 5 and 45 V and can handle currents up to 2 A. This is expected to be enough to control the motors, since the current they need without load is 0.5 A, and they load on the motors is not expected to be so large that the 2 A is exceeded.

The transistor that is chosen for the motor driver is of the type 50CN10N [29]. This transistor can handle 20 A drain current, and a gate source voltage of 20 V, meaning that it can handle the current and voltage that the motors require. It also has a typical gate threshold of 3 V, meaning the 3.3 V of the microcontroller should be able to switch it.

3.5. SOFTWARE

Now that all separate components are designed and chosen, the next step is to make all parts work together as one system. For our purposes, the microcontroller has five tasks to fulfill:

- The microcontroller reads out the location sent by the GPS module.
- The microcontroller keeps track of the orientation of the prototype using the data from the gyroscopes.
- The microcontroller calculates the direction the prototype has to face to travel to its destination.
- The microcontroller sends out the control signals for the motor drivers, for the appropriate propulsion in the calculated direction.

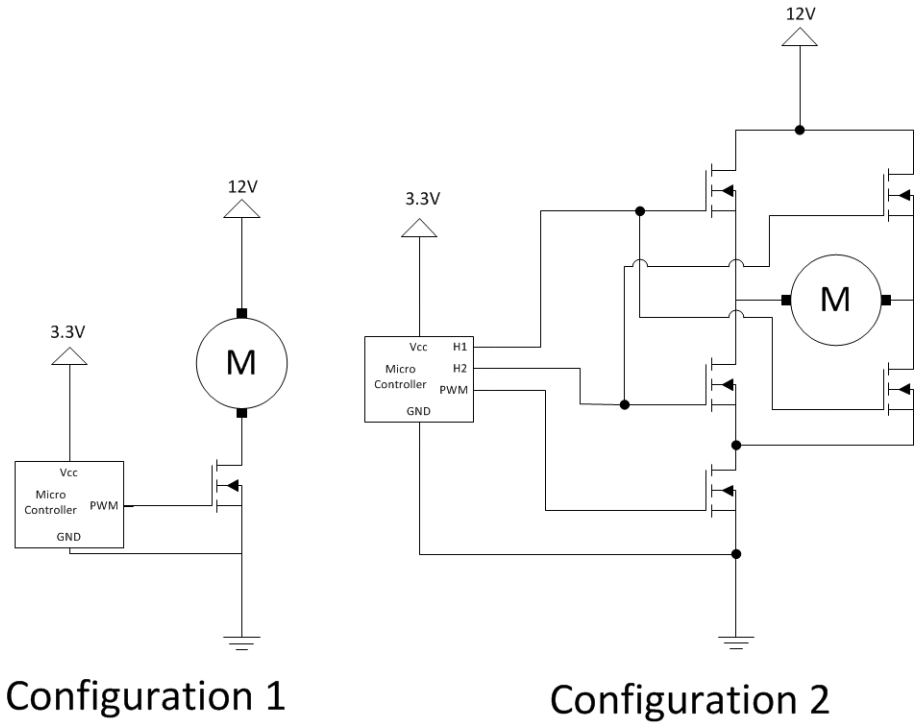


Figure 3.4: Implementation of the motor driver with just one NMOS transistor (configuration 1) and with an H-bridge in addition to the NMOS transistor (configuration 2)

- The microcontroller has a function that can be used to manually control the prototype.

3.5.1. COMMUNICATION WITH THE GPS MODULE

Setting up the communication with the GPS module is done by enabling the UART of the microcontroller and setting it to the correct baud rate. Like mentioned in section 3.2, the GPS module has a baudrate of 38400. The microcontroller has a baudrate generator that requires a input clock of 16 times the baudrate. The clock can be set to the desired frequency using a clock divider that controls the clock speed of the baudrate generator. Equation 3.2 shows how the value of this clock divider can be chosen: r_{baud} represents the desired baudrate, f_{clk} represents the clock frequency of the microcontroller and div represents the value of the clock divider. Solving for the unknow values results in a div of 117.1875. Setting the clock divider to 117, the closest integer to the desired value, results in a baudrate of 38462, which deviates 0.16% from the baudrate of the GPS module. This difference is small enough to ensure successful communication between the GPS module and the microcontroller.

$$r_{baud} = \frac{f_{clk}}{div * 16} \tag{3.2}$$

The bytes that are received using the UART form sentences of the NMEA-0183 protocol, as mentioned in section 3.2. The bytes represent symbols following the ASCII encoding. NMEA sentences always consist of comma-separated words. The first word of the sentence is a six-symbol-long word that starts with '$GP', while the three last letters of this word signify what kind of sentence that sentence is. A NMEA sentence ends with a '*' symbol, a checksum number and two end sentence symbols. The checksum number is a hexadecimal number that is used to verify that the received sentence does not contain a bit fault. The checksum must be equal to the xor of all received characters between the '$' and '*' symbols. If the checksum verifies the sentence, the information of that sentence can be used by the microcontroller.

There are a large amount of NMEA sentences, of which several are sent out by the GPS module. The communication is, for this purpose, one way: there is no need to communicate anything back to the GPS module, since it already sends useful sentences. The sentence that is primarily used to obtain the position and state of the GPS module is the '$GPGGA' sentence. This sentence contains the longitude and latitude of the module,

the amount of satellites in view and whether the module has a fix on its location. The longitude and latitude are represented in degrees, minutes (one sixtieth of a degree) and 10^{-4} minutes. Since $1 * 10^{-4}$ degree is the smallest value that can be represented in NMEA, the longitude and latitude values are stored on the microcontroller in a 32 bit register where one bit represents $\frac{1}{600000}$ degree. This means the resolution of the stored location is $\frac{1}{360 \times 600000}$ times the earth's circumference, which results in a resolution of 18.5 cm. This resolution is far smaller than the expected average difference between the actual position and the one measured by the GPS unit, which means this resolution will not be a limiting factor for the accuracy of the positioning.

The coordinates sent by the GPS module are expected to be varying to some degree, which will result in a rapidly changing current position that is used by the microcontroller. To prevent this, the current position that is used by the microcontroller will be the average of four received coordinates, which mean the position is updated once a second.

The GPS module can also calculate the orientation and speed of the buoy by comparing a number of previous locations. This data is only reliable when the module is moving fast enough for the previously visited points to form a consistent line. The prototype is expected not to move this fast, this is why the direction in which the prototype moves is measured using the gyroscopes.

3.5.2. COMMUNICATION WITH THE GYROSCOPES

The communication with the gyroscopes is, as mention before, done via the I^2C protocol. This protocol allows a 'master' to communicate with multiple 'slaves' over one shared bus [30]. In our application, the microcontroller acts as the master while both gyroscopes are slaves. The I^2C protocol uses 2 buses: one data bus over which the communication happens, and one clock bus. On the clock bus, a clock signal is set by the master, all slaves use this clock rate for the communication, making it synchronous communication. The microcontroller sets the clock rate of the I^2C bus to 400kHz. The specifics of the protocol can be found here [30], and will not be explained into more detail in this thesis.

3.5.3. DIRECTION CALCULATION

The microcontroller needs to be able to calculate the direction in which the buoy must sail in order to reach its destination. When neglecting the effects of the curvature of the earth, the direction in which the buoy needs to sail can be easily calculated using equation 3.3. L represents the longitude in this equation, while λ represents the latitude and θ represents the direction. Subscript c denotes the current position of the buoy and subscript d denotes that of the destination. The atan2 function is a function with two arguments that increases the range of the inverse tan function to $(-\pi, \pi]$, in the way shown in equation 3.5. When the curvature of the earth is not neglected, the fact that longitude and latitude are polar coordinates influences the equation, resulting in the more complicated equation 3.4. In the full-scale design, the route the buoy will take is calculated on a computer and sent to the buoy as a series of way points. This computer program uses data on sea-maps and shipping lanes, and does not lie within the scope of this thesis. The distance between the way points sent to the buoy will not be more than 20km, because the buoy does not sail very fast, so it will be travelling a long time between way points. The effect of the curvature of the earth when calculating the angle between two point less than 20 km apart is negligible. The prototype will, for testing purposes, never be given a destination more than several dozens of meters away, because of the limited length of the cable of the power supply, and the limited sailing area on the test location. This means equation 3.3 can be used to calculate the direction in case of the full-scale design as well as for the prototype. The main problem that needed to be solved is that the microcontroller has no hardware to do floating point calculations. As a result, the arctan function needs to be estimated just using integer operations.

$$\theta = atan2(L_d - L_c, \lambda_d - \lambda_c) \tag{3.3}$$

$$\theta = atan2\left(sin(L_d - L_c)cos(\lambda_d), cos(\lambda_c)sin(\lambda_d) - sin(\lambda_c)cos(\lambda_d 2)cos(L_d - L_c)\right) \tag{3.4}$$

$$arctan2(y,x) = \begin{cases} \arctan(\frac{y}{x}) & \text{if } x > 0 \\ 90° + \arctan(\frac{y}{x}) & \text{if } y \geq 0 \text{ and } x < 0 \\ -90° + \arctan(\frac{y}{x}) & \text{if } y < 0 \text{ and } x < 0 \end{cases} \tag{3.5}$$

The arctan function can be estimated using the CORDIC Trigonometric Computing Technique [31]. The computing sequence that is used by the microcontroller is the vectoring computing sequence. This sequence

rotates a two-dimensional vector with set angles, each one smaller than the previous one, until the vector lies as close as possible to the positive x-axis. By adding up all the taken rotation steps, the angle of the vector with the x-axis is obtained, which is equal to arctan(y/x). An example of how the vectoring sequence works, is shown in figure 3.5: the original vector (red) is rotated with increasingly smaller steps (blue) toward the positive x-axis.

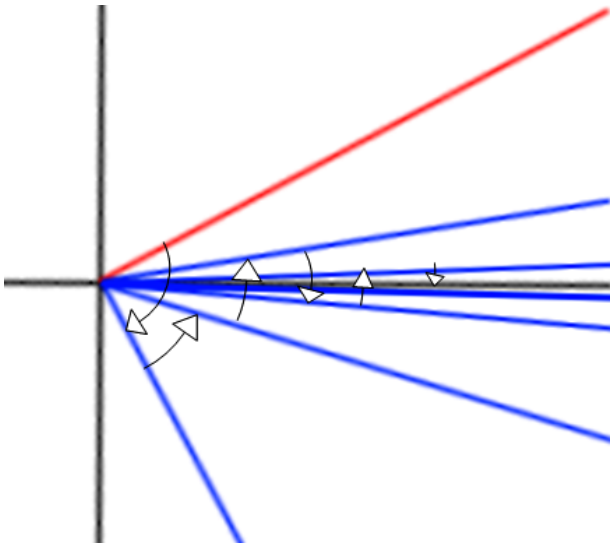


Figure 3.5: Example of the vectoring computing sequence.

The pseudocode representing the CORDIC vector step is as follows:

```
angle = 0
if y is larger than 0
    rotate 90 degrees clockwise (x = y and y = -x)
    angle = angle + 90
else
    rotate 90 degrees counter-clockwise (x = -y and y = -x)
    angle = angle - 90
iteration counter = 0
while the desired calculation accuracy is not met
    if y is larger than 0
        rotate arctan(2^iteration counter) degrees clockwise
        angle = angle + arctan(2^ -(iteration counter))
    else
        rotate arctan(2^iteration counter) degrees counter-clockwise
        angle = angle - arctan(2^ -(iteration counter))
    iteration counter is increased by 1
```

The angle that is added or subtracted each iteration is $\theta = arctan(2^{-n})$, because this way, each rotation step can be calculated by adding or subtracting a n-bit right-shifted version of each element of the vector to or from the other one. For example, a clockwise 45 degree angle is done by adding y to x and subtracting x from y, and a counter-clockwise rotation of 14 degrees ($arctan(1/4)$) is done by subtracting y, shifted right by 2 bits, from x and adding x, shifted right by 2 bits, to y. During this computing sequence, the length of the vector is not kept the same, but that information is not required.

To make the result of the vectoring sequence comparable to the rotation around the z-axis measured by the gyroscope, the angles of both the gyroscopes as the calculated direction need to be encoded in the same way. The orientation measured with the gyroscopes is saved in a register with the least-significant bit representing 35/2000 degrees. This is why the rotation values of the vectoring steps (90, 45, 26.6, 14.0 etc.) are calculated in the same format, and set hard coded into the memory of the microcontroller. These values will be used during the vectoring computing sequence: after each rotation the value corresponding to that rota-

tion is added or subtracted to or from the resulting angle.

With the vectoring computing sequence and equation 3.3, the direction towards the destination can be calculated. The last step is using this information to control the motors.

3.5.4. MOTOR CONTROL

The microcontroller must finally be able to send signals to the motor drivers. For each motors, there are two H-bridge control signals and one PWM signal that need to be sent out by the microcontroller. The values of these signals depend on the orientation and the desired direction of the buoy. The first step that the motor control algorithm takes, is calculating the angle the buoy still needs to rotate, which is done by subtracting the orientation from the direction. Using this angle, the motor control sets the duty cycles of both motors to a desired value. In this process, six states are defined: forward fast, forward slow, backwards slow, turn right and turn left. These states are called motor driver states, since each state causes a different behaviour of the motor driver. The forward fast state is used when the prototype needs to move to a new location, while the forward slow and backwards slow states are used when the prototype needs to keep a certain position, and when it has almost reached its destination. Turn left and right are used to turn the buoy in the right direction, before it can begin sailing toward its destination. These states will make the buoy turn around its z-axis without moving in the x of y directions. Finally, the stop state stops both motors. The prototype is in this state when it has reached its destination. With these six states, the prototype can reach any destination that is in a straight line from it. Table 3.2 shows the duty cycle of the PWM signals and control signals of the H-bridges that are required in each state.

State	Duty Cycle Left	H-bridge Left	Duty Cycle Right	H-bridge Right
Forward fast	100%	10	100%	10
Forward slow	50%	10	50%	10
Backward slow	50%	01	50%	01
Left	100%	01	100%	10
Right	100%	10	100%	01
Stop	0	00	0	00

Table 3.2: The PWM duty cycles and H-bridge control signals in each of the five motor driver states.

The motor control only needs to direct the prototype to a new location when it is further away from its goal then a set allowable drifting distance. This distance needs to be as small as the accuracy of the GPS module allows, according to requirement 2.1.11, so it needs to be chosen after the accuracy of the GPS module has been tested (see section 4.1.3). The absolute distance between the current position and destination could be calculated by the microcontroller, to see if the prototype must move, but this is not necessary. Instead, the motors are activated when the current longitude or current latitude differs more than a to be chosen value from the destination longitude or latitude respectively. The value must be chosen in such a manner that the maximum difference between the current position and destination is not more than the accuracy of the GPS.

3.5.5. THE OVERRIDE FUNCTION

The last thing the navigation software need to be able to do is be controlled remotely. Unfortunately, no real-time connection between the microcontroller and a computer could be implemented. Further research into I^2C communication with two masters could be done and a USB-to-I^2C connector purchased to make such a connection possible. And, due to the limited amount of pins available on the microcontroller board, a system that would control the prototype using for example the buttons on the microcontroller board was also not possible. However the function to turn off the autonomous position control and to enable a different piece of software to set the motor driver state of the prototype, is implemented. This function has two parameters, one that enables or disables the override function (1 is enabled, 0 enables the autonomous positioning) and one that represents what the motor driver state the controller should be in, if the override is enabled.

3.6. OVERVIEW DESIGN

Figure 3.6 gives an overview of the complete autonomous position control system as designed in this chapter. The PC power supply that is used to power the system, is not part of the design, since the power management falls outside the scope of the thesis. However, it is necessary for the system to function.

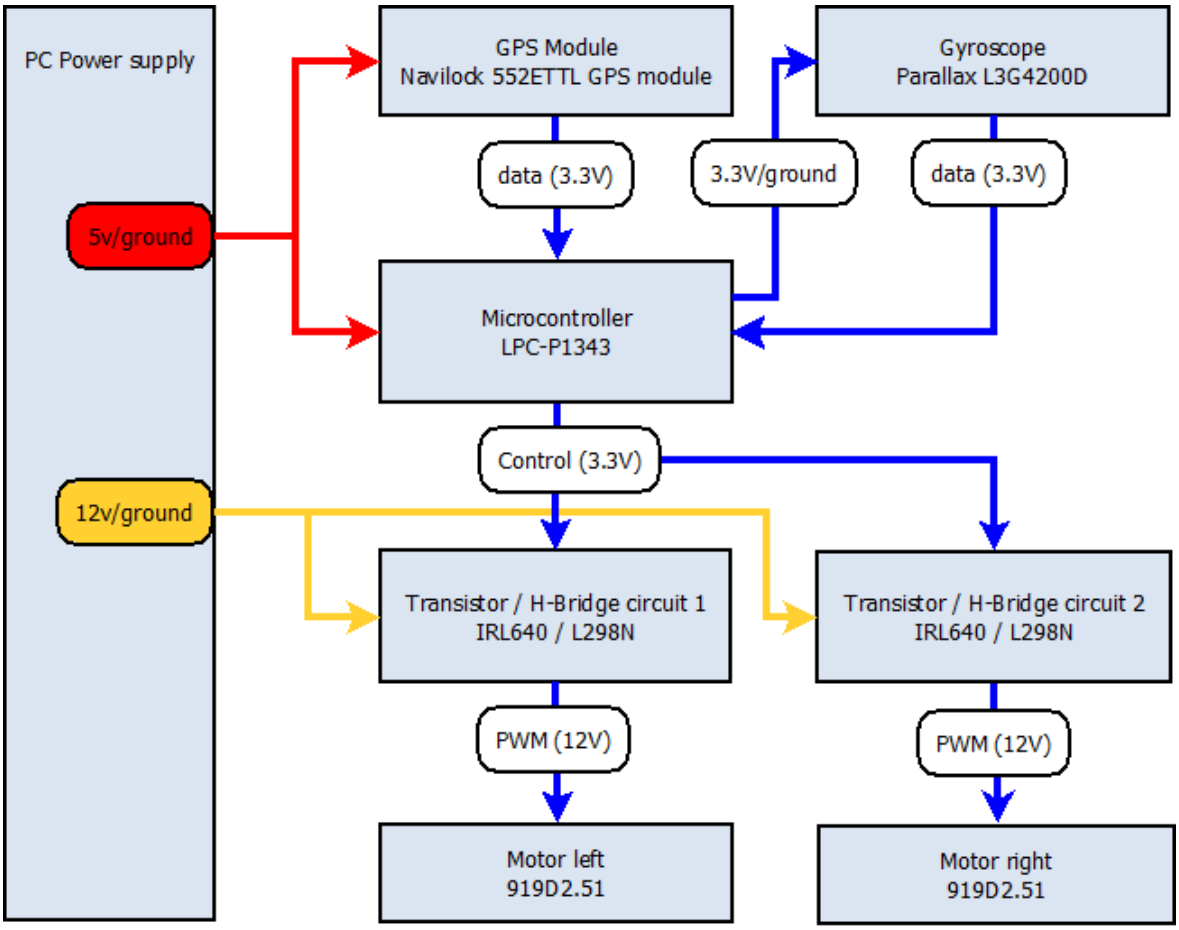


Figure 3.6: Total navigation system scheme

4

TESTING AND RESULTS

4.1. TEST PLAN

After completing the design, the construction phase starts. During the building process, tests are performed to check if the process goes right. These small tests will not be described. The tests that are performed at the completion of the construction of each component, are of more value and therefore will be described in following sections. The results of these tests are described, and compared with the requirements established in chapter 2. Finally, the system will be tested while integrated with the buoy.

4.1.1. MOTORS

Three tests were performed on the motors, in different stages of the design process, to verify that the design would work as expected:

- The first test on the motors is done shortly after the delivery of the motor. Supplying the motors with 12 V on their terminals in both ways, will reveal if the motors run in both directions, and then supplying the motors with a PWM signal supplied by a pulse generator at different duty cycles and frequencies, to observe how the motors react to PWM signals.

- The second test performed on the motors is a test to determine the difference between the two motors inside their casing. For this test, the motor is placed inside its casing and then directly connected to a voltage source. The propeller is not attached to it, because it does not contribute on the result. While supplying the motors with different voltages, the current used by the motors is noted. Although the power consumption is not a focus during this design, the motors may not use more than the 5.0 A, because that is the maximum current that can pass through the safety fuse, and the maximum current that may flow through the H-bridges is only 2.0 A.

- The third test is a test to determine if the waterproof casings are actually waterproof. Again, the propeller is not attached. The motor inside its casing is lowered into water and the source is turned on for several minutes at 12 V. Since the motor is the only component of the navigation system that is fully submerged, requirement 2.1.4 is tested during this test.

4.1.2. DRIVERS

Just as with the motors, three tests were performed on the motor drivers, in different stages of the design process:

- The first test is a test on the motor drivers alone to check that they were built correctly. This is done as follows: Voltage sources are used to power the drivers and to simulate the control signals of the H-bridges and a pulse generator is connected on the gate of the NMOS transistor to simulate PWM signals. The output of the H-bridges is measured to confirm that the motor driver works as expected.

- If this first test succeeds, the same test is done with the PC power supply to power the motor driver and the microcontroller to provide the control signals.

- As a last step, the motors are connected to the output of the H-bridges. The motors are inside their waterproof casing during this test. By checking if the motors rotate at the expected speed and in the expected direction, it can be verified that the drivers work correctly. The limitation that needs to be taken into consideration during this test is that the H-bridges can only conduct 2 A of current without risking them breaking.

4.1.3. THE GPS MODULE

The first test conducted with the GPS module is a test to determine the accuracy of the module. For this test, the GPS module is connected with a PC using a USB TTL serial cable. This cable converts the serial signal sent into the USB end to a UART signal and vice versa. The 5 VDC on the USB port is also used to supply the GPS unit with its required power. The test is performed outdoors, because the GPS module does not have a strong enough signal from enough satellites inside a building to calculate its position reliably. During the test, ten samples are taken from the GPS output signal over a period of several minutes. The coordinates of each of these samples are compared to each other and to the actual position from which the test was done. The coordinates of the positions where the test is done, are obtained using Google maps. The test is done two times in two different locations to determine the effect of the surroundings in which the test is done. The first test is done in a location that is on three sides surrounded by buildings, while the second test is done in a location with fewer buildings in the vicinity. The main requirement that is tested during this test is requirement 2.1.8, which says that the average deviation of the positioning system should not be more than 10 m.

4.1.4. NAVIGATION

The navigation system is the combination of the GPS, a gyroscope and the microcontroller working together to determine the direction in which the buoy has to go to reach its destination. During the design, all components were first tested separately:

- The GPS module is attached to the microcontroller and to a pc using a UART-to-USB cable. The microcontroller displays the received GPS coordinates on the LEDs which can be checked to the coordinates received by the pc.
- The gyroscope is attached to a flat surface and after calibration it is rotated several times around its z-axis. The microcontroller displays the measured angle on its LEDs, so that the actual rotation can be compared to the measrued rotation.
- The direction calculation is tested by programming several current positions and destinations into the microcontroller, and displaying the result on the LEDs to be checked against the expected values.

After all components were tested to work separately, the total navigation system is tested. For this test, both the GPS and and gyroscope are connected to the microcontroller. The GPS module, the two gyroscopes and the microcontroller are fastened closely together on a piece of wood, as shown in figure 4.1. The system on this piece of wood will be called the navigation module during this test. One end of this 'module' is chosen to be the front: this would be the direction the buoy would sail if the module was mounted on the prototype. Both gyroscopes are present, although only one is necessary, because the software is designed to initialize and communicate with two gyroscopes. Changing this would take time, while initializing an extra gyroscope, but not using it, does not have any negative effects.

A destination position is chosen: the coordinates of that destination are measured using the GPS module, and entered into the software. Then a start position is chosen a several dozens of meters from the destination. During this test, the different motor driver states are represented using the LEDs on the microcontroller: when the LEDs in the middle of the array of 8 LEDs light up, it is in the forward state. Light on the left and right op the module (when pointing the front side of the module away from you) means that it is in the left and right states respectively. All LEDs lighting up at once means that the destination has bee reached.To let the gyroscope put out the orientation of the navigation module in degrees from true north, like the direction calculation does, the gyroscope needs to be initialized while the navigation module points straight north. This is verified using a compass.

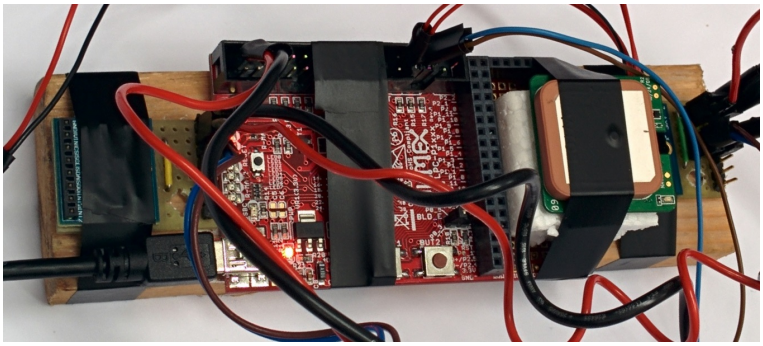


Figure 4.1: Test setup for the complete navigation system.

After initialization, the navigation module is moved in the same way the buoy would in the motor driver state that is represented on the LEDs. The position on which the stop state is entered is compared to the actual destination position. If the stop position of is less than the GPS accuracy away from the desired destination, then the test is successful, and then requirement 2.1.9 is met.

4.1.5. TOTAL SYSTEM

The total navigation system must be weighed to determine its exact mass, to check if requirement 2.1.6 is met. This will be done with a kitchen scale. Other test on the total navigation system are done with the system integrated with the prototype of the buoy.

Requirement 2.1.12 states that the system needs to have an override function, for maneuvering the buoy manually or any other purposes. The implementation of this function is described in section 3.5.5. This function will not be tested explicitly, but it will be used during tests involving the motor driver and the microcontroller, to simulate the motor driver states calculated by the autonomous positioning. This is done by connecting the motor drivers to the microcontroller and using the override function on the microcntroller to set the output signals to a certain motor driver state using the buttons on the microcontroller. If those tests are successful, requirement 2.1.12 will be met as well.

4.1.6. INTEGRATED SYSTEM

After the autonomous positioning system has been tested on its own, the system is installed on the prototype of the buoy, which is designed by M. Baas & A. Pannekoek [10]. The motors are placed in the chosen configuration on the underside of the buoy, as figure 4.2 shows, and the microcontroller and drivers are placed inside the PVC drain pipe that forms the center of the prototype. The PVC pipe can be sealed, making it splash-water proof. Therefore requirement 2.1.5 is considered met.

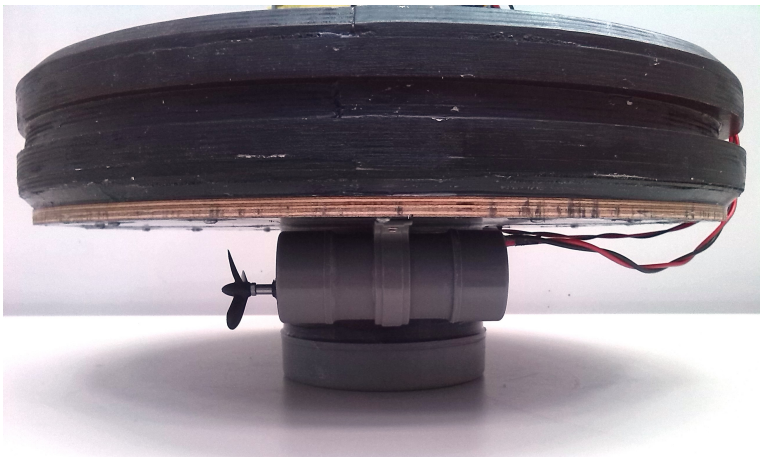


Figure 4.2: The motors attached to the prototype of the buoy.

The buoy is tested in the top end of the towing tank of the faculty 3ME of Delft University of Technology. During this test, all motor driver states are tested to see if they make the buoy move as they should. While testing each state, the forward or rotational speed in that state is measured. During this test, the PC power supply is placed on the buoy to power the prototype. The testing setup is shown in figure 4.3. The 230V cable the leads to the power supply is made sure not to touch the water. And to minimize the effects if the cable might touch the water and short-circuit through the water, a 230 V to 230V transformer with earth leakage switch and fuse is installed between the power supply and the power socket. During this test, requirement 2.1.14 will be checked. This requirement states that the autonomous navigation control can not destabilize the prototype. This is tested by checking whether the prototype with the autonomous position control system can be easily capsize. If this is not the case, the requirement will be met.

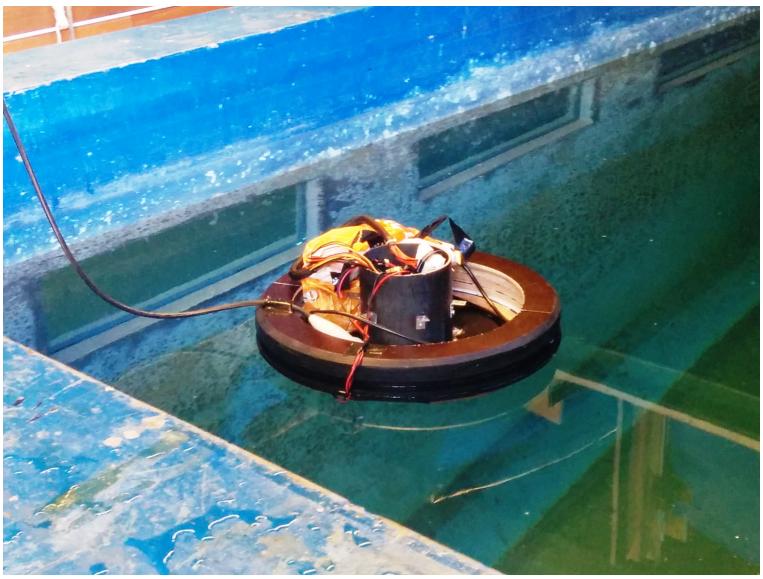


Figure 4.3: Testing the speed and turning of the buoy

Another test was done to test the entire autonomous positioning system in combination with the buoy. For this test, a cable of the pc power supply was extend to 10 meters in length. This way the power supply does not need to be on the buoy, meaning that the fuse in the power supply will cut off the power if a short circuit occurs due to water. The combination of the GPS, gyroscopes and microcontroller, as shown in figure 4.1, is placed on top of the prototype, and the motor drivers are connected to the microcontroller. A destination position is pre-programmed into the microcontroller. Then, the buoy is laid into the water about 25 m away and then turned on to see if it moves towards its destination.

4.2. RESULTS AND DISCUSSIONS

The tests described in the previous section, are performed and results are described in the this section. After the test results, the consequences of the results of the tests are discussed.

4.2.1. MOTORS

The result of the motor tests is that the motors worked fine and the casings are both watertight. After rotating for several minutes under water at full speed, no water had leaked into the casing. The casings do add some friction on the motor shaft, making the current that the motors require during their start-up more than 2 A. To differentiate between the two motors, they are mentioned by the position they will be given on the prototype: left or right. The first seconds, the right motor used 2.1 A while the left motor used 2.5 A, with peaks at the moment of switching that were even higher. After the start-up, the current through both motors slowly declined toward 1.3 A through the right motor and 1.9 A through the left one. This difference in power consumption is caused by the way each motor is fastened into its casing: the left motor was placed slightly obliquely with respect to the tube, increasing the friction of the rubber ring on the rotor shaft. The decrease of the current is due to the warming up of the petroleum jelly, which causes less friction. In table 4.1, currents at different PWM signals are noted. The start-up current (the first few seconds after switching on the motor)

is not captured in the table.

Duty cycle [%]	Current motor left [A]	Current motor right [a]
25	stall	stall
40	stall	stall
50	1.8	2.1
75	1.8-2.0	1.5-2.2
85	1.8-1.9	1.6-1.7
100	1.9-2.0	1.3-1.6

Table 4.1: Measurement of currents at different duty cycles and 500 Hzat 12 V

4.2.2. DRIVERS

The first test confirmed that the motor controllers work the way they were supposed to: The output during this test was a PWM signal of 12 V with the same duty cycle and frequency as the input set by the pulse generator.

At the second test, it was discovered that the transistor 50CN10N is virtualy unable to switch on at the voltage of 3.3 V that the microcontroller supplies. After replacing the transistors with the type IRL640, the last test was done. Properties of this transistor can be found in appendix B

After connecting the motors, the current increased and became too big for the H-bridge to handle, more than 2 A as shown in table 4.1. The H-bridge temperature rose up until 100 °C and kept rising. The large current was caused by the resistance of the casings. That is why the choice could be made to use an other H-bridge which can handle bigger currents. Due to limited time, the H-bridge was removed from the motor drivers during all further tests, causing the buoy to rotate around the Z-axis with a drift of at most 0.5 m. Therefore, requirement 2.1.13 is not met, but consequences are very limited: No other requirements are endangered and the buoy is still properly maneuverable. The test with the transistor as the only component in the driver circuit, had a good result. The circuit that is instead, is shown in figure 3.4, configuration 1. Not all states of the motor controller (described in section 3.5.4) be used without the half bridges. Table 4.2 shows which states can still be used without the H-bridges. The states are different in another way from the states from table 3.2 in the way that the left and right states only use a 50% duty cycle. Since the rotation speed of the prototype will not be the maximum possible without H-bridges, the choice is made to reduce the rotation speed even further, in favour of higher controllability.

State	Duty Cycle Left	Duty Cycle Right
Forward fast	100%	100%
Forward slow	50%	50%
Left	0%	50%
Right	50%	0%
Stop	0	0

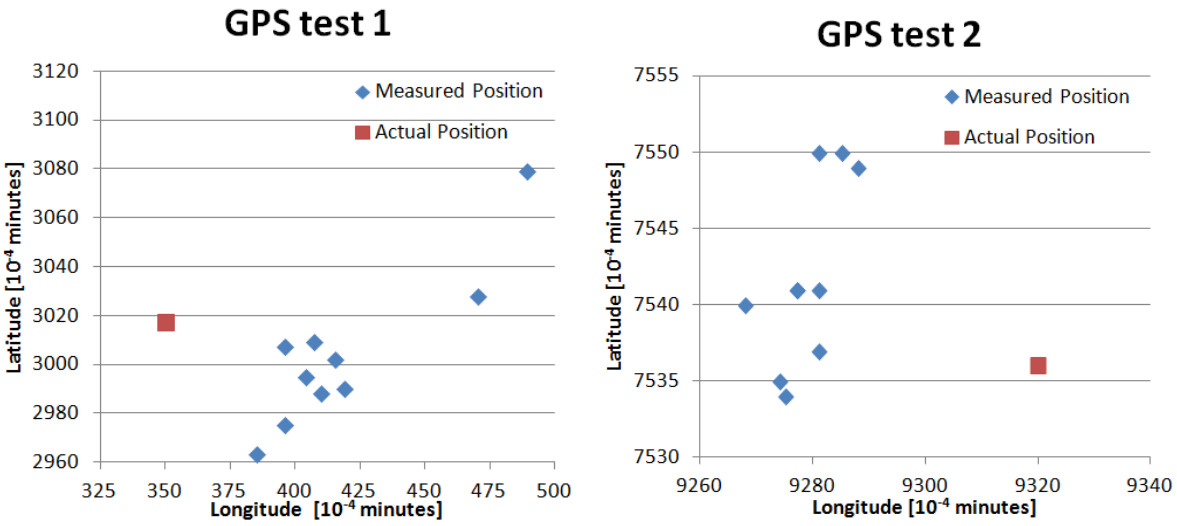
Table 4.2: The PWM duty cycles in each of the motor driver states that remain withou H-bridges.

4.2.3. THE GPS MODULE

During the first test, the amount of satellites in the view of the GPS module varied between four and seven, averaging 5.5 satellites. The coordinates from the ten samples taken during this test are shown in figure 4.4a. The measured points have a standard deviation of 0.00336 minutes from the average latitude value and a standard deviation of 0.00318 minutes from the average longitude of the measurements. This average coordinate of the ten samples lies 0.0069 minutes latitude and 0.0013 minutes longitude from the coordinates of the actual measurement position. 10^{-4} minute is, as mentioned in section 3.5, equal to 18.5 cm, when is assumed that the circle of which that length is a part, has the circumference of the earth. This is the case for the longitude circles, which go over both poles, and the latitude circles, which are perpendicular to the longitude circles, near the equator. But the circumference of latitude circles decreases as the distance to the equator increases. This means, when assuming 10^{-4} minute is equal to 18.5 cm, this will always be a maximum value. Thus, the average distance between the measured positions and the actual position is at most 13

m. ($\sqrt{69^2 + 13^2} * 0.185$)

During the second test, the GPS module had seven satellites in its view during all samples. The coordinates from the ten samples taken during this test are shown in figure 4.4b. The measured points have a standard deviation of 0.00057 minutes from the average latitude and 0.00060 minutes from the average longitude of the measurements. The average coordinate of the ten samples lies 0.0041 minutes latitude and 0.0006 minutes longitude from the coordinates of the actual testing position. This means that the average distance between the actual position and the measured positions is at most 7,9 m. Based on the result of both tests, the maximum drift-off distance, as described in section 3.5.4, is chosen to be 10 m. Based on this choice, the motor controller will start the motors when either the longitude or latitude of the current position of the prototype is $17 * 10^{-4}$ GPS minutes different from that of the destination. This allows a maximum drift either straight north, south, east or west of 3.23 m, and a maximum distance diagonally of 10.4 meter.



(a) Results of the first GPS test

(b) Result of the second GPS test

Figure 4.4: GPS location deviation tests

The main problem with the result of this test is that the actual coordinates of the position where the tests were done, came from a source of which the accuracy is unknown. Even when using the satellite images of Google Earth, it cannot be verified that the coordinates obtained by requesting the coordinates of a point on the map, are the exact coordinates of the testing position. This means the amount of distortion on the measured position cannot be determined with 100% accuracy. The noise on the measured position, on the other hand, is measurable by calculating the standard deviation of the measurement.

The conclusion that can be drawn from these measurements is that the accuracy of the GPS module is dependent on the amount of satellites in view, which in turn is dependent on, among others, the location of the GPS module. The more open the surroundings of the GPS module are, the easier the module can pick up signals from satellites. In the second test, this effect was visible by the lower standard deviation of the the points from the average. The full-scale buoy will be sailing at sea, an environment with very little obstructions like buildings, which means the GPS will not be hindered by this kind of obstructions. This makes the second test more representable for the conditions under which the buoy will be operating. That means that that the requirement 2.1.8 is met: the positioning system has an average deviation of less than 10 m.

4.2.4. NAVIGATION

The tests performed on the separate parts of the navigation system yielded the following results:

- The communication between the GPS module and the microcontroller works as intended: the slight difference in baud rate did not have a noticable negative influence on the communication.
- The angle measured by the gyroscope has a slight error that is linear to the amount the gyroscopes

has turned from the position in which it was calibrated. After correcting this error by multiplying the measure angle with a constant value of 1.02, the average measurement error was reduced to around 2 degrees. The results of this test are displayed in table 4.3. The error might be caused by the gyroscope not being exactly horizontal during the tests. If this is the case, more accurate orientation measurements would require to be compensated for the effects of x and y rotation. However, the source of the error was not conclusively found.

- The directions calculated by the microcontroller was during all tests less than half a degree away from the expected direction.

Rotation [degrees]	Error without correction [degrees]	Error after linear correction [degrees]
720 clockwise	34	3
720 counter-clockwise	30	2

Table 4.3: The measured angle error after 2 full rotations without and with linear correction.

The testing of the navigation system showed that the navigation system can direct the prototype successfully to a given destination. By turning according to the left and right states, and moving straight ahead in the forward state, the intended position was approached, and when it was close enough, the stop state was entered. The distance between entering the stop state and the intended position varied between 3 and 10 meters, depending on the direction from which the destination was approached. Interesting about this test is that the destination was not approached in a straight line, but in slight spiral-like curve. This resulted in a taken path that is 50 meters, while the distance between the start and destination was only 40 meters. This deviation is most likely caused by the fact that the gyroscope was not calibrated while the module pointed exactly north. This happened because the compass could not be held directly next to the module before calibration, because the electromagnetic field of the laptop, that was used as power source for the navigation system, influenced the compass. Since the navigation system reached its destination, requirement 2.1.9 is met.

4.2.5. TOTAL SYSTEM

One motor with its cables has a mass of 383 g and the drivers have a mass of 56 g. That adds up to 882 g. The mass of the microcontroller was not taken into account, because the microcontroller is already on site. Even if the microcontroller was added, the weight would not exceed 1 kg and therefore requirement 2.1.6 is met.

4.2.6. INTEGRATED SYSTEM

The first test after lowering the prototype into the water is testing if it is still stable on the water's surface with the autonomous position control system attached. Since the buoy remained floating right-side up, even when pushed over, it was confirmed that the prototype was still stable. With this, requirement 2.1.14 is met.

Each motor driver state is tested and measured twice. In table 4.4, the average speeds measured during the tests are shown, in case of the forward states, or the average turning speeds in case of the turning states are shown. One motor was found to provide less thrust than the other. The effect of this was that the buoy did not sail in an exact straight line at the slower speed. Also the rotation one way around was slower than the other way around. These effects can be prevented by choosing more suitable PWM values for the affected states. All values of the table are obtained with the buoy being stationary at the start of the test. The real top speed is therefore higher than the values shown in the table. It can be concluded that requirement 2.1.7 is met.

Duty cycle [%]	speed [m/s]	Duty cycle [%]	Rotation speed [degrees/second]
100	0.62	50 (left turn)	56
50	0.31	50 (right turn)	37

Table 4.4: Results of testing the speed and turning of the buoy

The test of the entire autonomous positioning system did not yield any results other than the observation that the test setup was flawed. The motors rotated far slower in this setup than in previous tests, needing the

full 100% duty cycle on the PWM signals to begin turning, and even then they did not always start rotating. This can be attributed to the voltage drop that occurs when up to 4 A of current travels through 10 meter of copper wiring.

The requirements 2.1.10 and 2.1.11 are a combination of the GPS accuracy measurement and the navigation system tests. Requirement 2.1.10 states that the prototype must be able to reach its destination as accurately as the GPS allows, and 2.1.11 states that it must be able to keep its position with that same accuracy. Since the GPS measurements revealed that the accuracy of the GPS unit is less then 10 meters, the navigation was designed to only kick in when the distance to the destination is more than that. It is also tested that the navigation can notice when it is further than this distance away from its destination. This means we can deduce that requirements 2.1.10 and 2.1.11 are met.

The total navigation system costs €134.22, which not include the gyroscope. The budget granted was €70. It must be noted that the estimated budged differed quite a bit with the final expenditure. Costs for raw materials were barely made and besides that, the other group members chose a design that turned out to be cheaper than expected. With shifting some budget, the costs stayed under limit. Requirement 2.1.3 is therefore met.

Component (amount)	Name	Price	Origin
Microcontroller board	Olimex LPC-P1343	Borrowed	DUT
GPS unit	Navilock 552ETTL GPS module	€39.99	Conrad Electronic Benelux BV
GPS cable	Aansluitkabel Navilock NV-DL-Z	€9.99	Conrad Electronic Benelux BV
Gyroscope	Parallax L3G4200D	€26.29	RS Components B.V.
Nmos transistor (2)	IRL640PbF	2×€3.95	HEC Electronica Delft
Brushed motor (2)	919D2.51	2×€26.06	RS Components B.V.
Waterproofing materials	PVC caps,clips and glue & other material (see fig.3.3)	€13.94 & free	Gamma & DUT
Propeller(2)	3-bladen scheepsschroef (2308.50L)	2×€3.89	Conrad Electronic Benelux BV
Fuse with socket(2)	5 A fuse with socket	2×€1.25	HEC Electronica Delft
PC power supply	Cooler Master RS-380-PMAP	Borrowed	Own input
Wires	Different colours/types	Free	DUT
Total		€160.51	

Table 4.5: components with their prices (Delft University of Technology is abbreviated as DUT)

5

CONCLUSION

In the problem definition (chapter 2), a number of requirements were set in order to achieve the goal of this thesis, which is designing autonomous position control for the SEAWATCH buoy. As can be read in chapter 4, the tests confirmed that all of these requirements are met, except for requirement 2.1.13. Since the compensation of the yaw would not be implemented anyway, because of the scope, and this requirement was aimed at making such compensation easier possible, it can be concluded that a successful prototype has been built.

The beauty of the design, is that it can be seen as a black box. If the gyroscope used is included in the package, the whole system can be placed on any buoy to create a navigation system. When implemented on other buoys, characteristics might change, like top speed, rotation speed and energy consumption.

Some parts of the system can easily be scaled up: the microcontroller can handle the NMEA protocol, making it able to communicate with almost any GPS receiver. The motor driver can be scaled up if high-power H-bridges and transistors are used. The propellers are scalable and would become 25 cm in diameter, but the motors are not scalable while also meeting the full-scale buoy requirements: If the motors would be scaled up, they would consume 1 kW of energy together, which is far more than the limitation on the power set by requirement 2.1.16. The tests have shown that the motors on the prototype could be smaller while still achieving the desired top speed, but even then the power requirement will most likely not be met on the full-scale buoy. In the recommendations (chapter 6), some suggestions are done to solve this issue.

The system designed is a rather orthogonal system. That means that different components of the system can be adapted or replaced without the other components being influenced. The microcontroller for example, could be updated with new software or replaced. A driver with a H-bridge could replace the current driver without consequences.

5.1. OVERVIEW SYSTEM

The design of the manoeuvring system of the buoy resulted in an autonomous navigation system. In table 4.5, all components used in this system are summarised with their price and origin.

- The microcontroller board calculates the route, a straight line to it's pre-programmed destination. It is able to do that on the condition that it receives its current location and orientation. After the calculation, the microcontroller outputs a control signal to the drivers.
- The current location is send by the GPS unit. Via an UART connection, the location is sent to the microcontroller board 4 times per second.
- The orientation is calculated from the data sent by the gyroscope.
- The drivers turn the 3.3 V PWM control signal to a 12 V PWM signal, and outputs it to the motors.
- The waterproofed motors, at last, run the propellers, making the buoy move.

6

RECOMMENDATIONS

Reviewing our design, a few things can still be improved, or need more research. A short list of possible developments is given:

- The motor drivers for the prototype need to be able to make the motors rotate both ways. For this the design with the first H-bridge could be modified with a H-bridge that can handle higher currents.
- To make the GPS data more accurate, differential GPS (DGPS) could be considered. For this technique, stations on land broadcast corrections on the GPS signals. These corrections can be used by the buoy to make its positioning more accurate.
- A way to do more accurate surge and sway corrections can be investigated. An accelerometer could used to more accurately measure the surge and sway, while a configuration with more motors might be able to do these corrections more accurately. These sensors could be positioned on the stabilized platform of the buoy to minimize measurement errors that may be caused by surge and sway motion.
- An electrical compass as an addition on the gyroscope, will prevent errors cause by integrating the noise on the gyroscope measurements.
- In the next design, the yaw correction could be implemented. A control system might be necessary to to control this yaw correction.
- The direction in which the destination lies, when it is calculated using the implemented method, can become inaccurate when the the distance to the destination and the distance of the buoy from the equator increase. Implementing an algorithm that utilizes equation 3.5 will solve this problem and ensure that the buoy always sails toward the destination via the shortest path.
- A way can be devised to transmit the coordinates of a new destination to the microcontroller remotely. Since both the UART and the I^2C connections are already used by the microcontroller, this could not be implemented in this prototype.
- Research could be done in different hull shapes for the full-scale buoy. The power required to propel the buoy is far higher than the available power. The motors could be smaller when the water drag of the buoy would be a lot smaller. A more streamlined hull will decrease the water drag.
- The full-scale buoy could also be equipped with a different source of power, such as fuel cells, to provide the power its needs for its autonomous positioning. Possibilities that can be considered is equipping the buoy with a small wind turbine, like some of the other existing LiDAR buoys, or covering more area of the buoy with solar panels.

A

Budget

BEGROTING

Versie 2

In dit document staat een globale begroting beschreven voor het Bachelor Afstudeer Project (BAP) met als onderwerp 'Manoeuvrable stabilised buoy for offshore wind assessment'. Er is gekozen voor een aanpak waarbij voor het manoeuvreren twee schroeven worden gebruikt, en voor het stabiliseren een platform met pneumatische cilinders. Het overzicht van onderdelen is niet compleet, omdat we sommige onderdelen in ons klein schaal model weglaten (zoals een gps unit) of voor sommige onderdelen (zoals bijvoorbeeld de accu) goedkope of gratis alternatieve 'oplossingen' gebruiken (zoals een spanningsbron).

PRODUCT	**AANTAL**	**PRIJS PER STUK**	**PRIJS**
Microcontroller	2	€20	€40
AD/DA omzetter	4	€10	€40
Actuatoren	4	€30 (+€80 eenmalig)	€200
Compressor	4	€30	€120
Sensoren	3	€50	€150
Printplaat	2	€20	€40
Overig (Raw materials)	1	€100	€100
Motoren	2	€15	€30
Post onvoorzien	1	€100	€100
TOTAAL	19		€820

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B

DATASHEET TRANSISTOR

On the next three pages, the most relevant pages of the datasheet of the used transistors [32] are included.

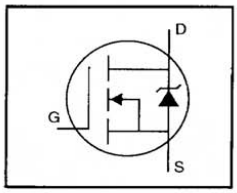
International
IOR Rectifier

PD - 94964

IRL640PbF

HEXFET® Power MOSFET

- Dynamic dv/dt Rating
- Repetitive Avalanche Rated
- Logic-Level Gate Drive
- $R_{DS(on)}$ Specified at V_{GS}=4V & 5V
- Fast Switching
- Ease of Paralleling
- Simple Drive Requirements
- Lead-Free



V_{DSS} = 200V

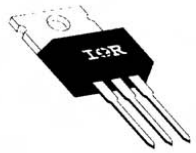
$R_{DS(on)}$ = 0.18Ω

I_D = 17A

Description

Third Generation HEXFETs from International Rectifier provide the designer with the best combination of fast switching, ruggedized device design, low on-resistance and cost-effectiveness.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 5.0 V	17	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 5.0 V	11	
I_{DM}	Pulsed Drain Current ①	68	
P_D @ T_C = 25°C	Power Dissipation	125	W
	Linear Derating Factor	1.0	W/°C
V_{GS}	Gate-to-Source Voltage	±10	V
E_{AS}	Single Pulse Avalanche Energy ②	580	mJ
I_{AR}	Avalanche Current ①	10	A
E_{AR}	Repetitive Avalanche Energy ①	13	mJ
dv/dt	Peak Diode Recovery dv/dt ③	5.0	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting Torque, 6-32 or M3 screw	10 lbf•in (1.1 N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	—	1.0	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	—	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	—	62	

Electrical Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	200	—	—	V	V_{GS}=0V, I_D= 250µA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.27	—	V/°C	Reference to 25°C, I_D= 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	0.18	Ω	V_{GS}=5.0V, I_D=10A ④
		—	—	0.27		V_{GS}=4.0V, I_D=8.5A ④
$V_{GS(th)}$	Gate Threshold Voltage	1.0	—	2.0	V	V_{DS}=V_{GS}, I_D= 250µA
g_{fs}	Forward Transconductance	16	—	—	S	V_{DS}=50V, I_D=10A ④
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	µA	V_{DS}=200V, V_{GS}=0V
		—	—	250		V_{DS}=160V, V_{GS}=0V, T_J=125°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS}=10V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS}=-10V
Q_g	Total Gate Charge	—	—	66	nC	I_D=17A
Q_{gs}	Gate-to-Source Charge	—	—	9.0		V_{DS}=160V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	38		V_{GS}=5.0V See Fig. 6 and 13 ④
$t_{d(on)}$	Turn-On Delay Time	—	8.0	—	ns	V_{DD}=100V
t_r	Rise Time	—	83	—		I_D=17A
$t_{d(off)}$	Turn-Off Delay Time	—	44	—		R_G=4.6Ω
t_f	Fall Time	—	52	—		R_D=5.7Ω See Figure 10 ④
L_D	Internal Drain Inductance	—	4.5	—	nH	Between lead, 6 mm (0.25in.) from package and center of die contact
L_S	Internal Source Inductance	—	7.5	—		
C_{iss}	Input Capacitance	—	1800	—	pF	V_{GS}=0V
C_{oss}	Output Capacitance	—	400	—		V_{DS}= 25V
C_{rss}	Reverse Transfer Capacitance	—	120	—		f=1.0MHz See Figure 5

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
I_S	Continuous Source Current (Body Diode)	—	—	17	A	MOSFET symbol showing the integral reverse p-n junction diode.
I_{SM}	Pulsed Source Current (Body Diode) ①	—	—	68		
V_{SD}	Diode Forward Voltage	—	—	2.0	V	T_J=25°C, I_S=17A, V_{GS}=0V ④
t_{rr}	Reverse Recovery Time	—	310	470	ns	T_J=25°C, I_F=17A
Q_{rr}	Reverse Recovery Charge	—	3.2	4.8	µC	di/dt=100A/µs ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is neglegible (turn-on is dominated by L_S+L_D)				

Notes:

① Repetitive rating; pulse width limited by max. junction temperature (See Figure 11)

② V_{DD}=50V, starting T_J=25°C, L=3.0mH R_G=25Ω, I_{AS}=17A (See Figure 12)

③ I_{SD}≤17A, di/dt≤150A/µs, V_{DD}≤$V_{(BR)DSS}$, T_J≤150°C

④ Pulse width ≤ 300 µs; duty cycle ≤2%.

International
IOR Rectifier

IRL640PbF

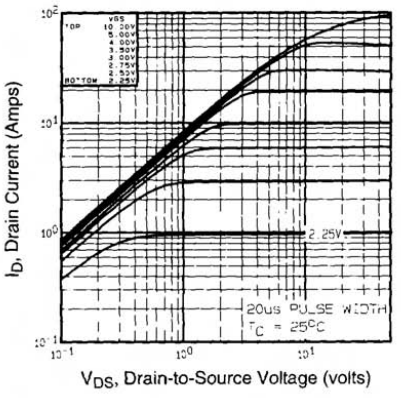


Fig 1. Typical Output Characteristics, T_C=25°C

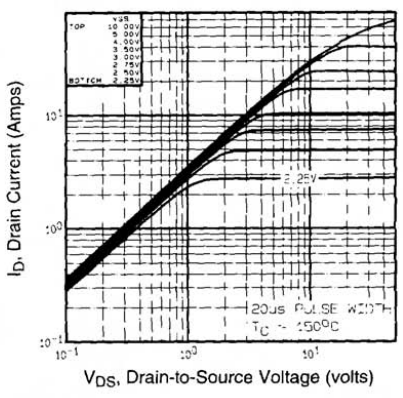


Fig 2. Typical Output Characteristics, T_C=150°C

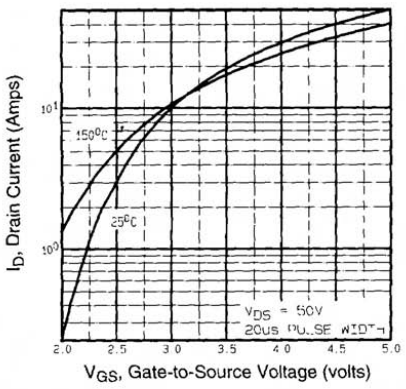


Fig 3. Typical Transfer Characteristics

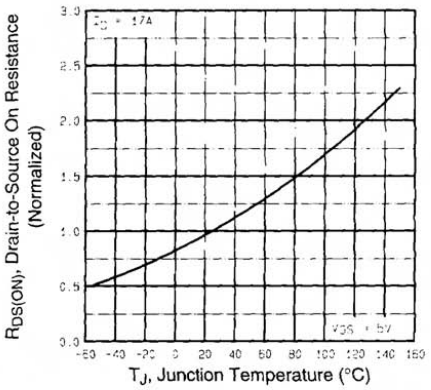


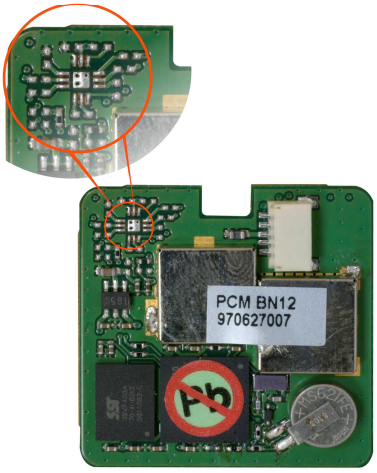
Fig 4. Normalized On-Resistance Vs. Temperature

C

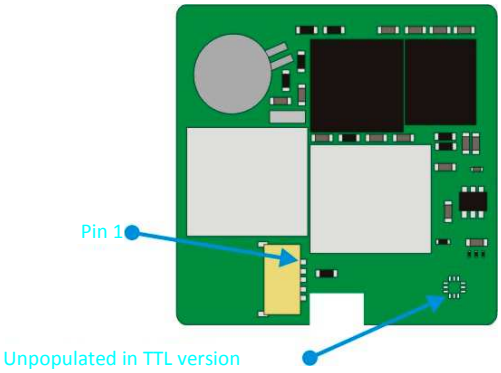
DATASHEET GPS MODULE

On the next three pages, the most relevant pages of the datasheet of the GPS module [25] are included.

NAVILOCK®



Pin	Assignment
1	+5 Volt
2	GND
3	Shield
4	3.3V TTL TX Level/Output
5	3.3V TTL RX Level/Input



NAVILOCK®

Please refer to u-blox5 Receiver Description / Protocol Specifications:
http://www.u-blox.com/images/downloads/Product_Docs/u-blox5_Protocol_Specifications%28GPS.G5-X-07036%29.pdf

See the Chapter Navigation Configuration Settings Description on page 42. You can configure it by use of u-center, or transmit it to the receiver by batch command every time the system starts up.

GPS modules NL-550ERS, NL-551EUSB, and NL-552ETTL are designed to “forget” all user settings, when the battery pack is low, to be able to meet demands of the broad range of private users who make adjustments whose effect they do not know. In order not to render the module unusable thereafter, the memory is volatile for user settings.

General Specifications

- u-blox5 GPS & GALILEO SuperSense® UBXG5000/UBXG0010 GPS Chipset
- High Sensitiv (Tracking Sensitivity: -160 dBm)
- AssistNow Offline Support (14 Days Almanac Data)
- DGPS, WAAS, EGNOS, and MSAS Support (EGNOS Default disable)
- Supports NMEA 0183 Protocol
- Internal patch antenna

Specifications

- Chipset: u-blox5 GPS & GALILEO SuperSense®
- Frequency: L1, 1575.42 MHz
- C/A Code: 1,023 MHz
- Channels: max 50 channels
- Position UP-DATE Rate: 4 Hz
- Sensitivity: -160 dBm Tracking
- Sensitivity: -160 dBm Satfixing
- Sensitivity: -145 dBm Cold Start
- Positioning accuracy 2.5 m CEP; 5.0 m SEP, or SBAS 2.0 m CEP; 3.0 m SEP
- Speed: 0.1 m/s
- Time: 1µs synchronized to GPS time
- Internal CMOS Multi-Purpose Flash 2^N Byte (13H = 19; 2^{19} = 512 KByte (SST39VF400A)

Date

- Basic setting: WGS-84

Time

- New acquisition: 1 sec. on average
- Hot start: 3.5 sec. on average
- Warm start: 25 sec. on average
- Cold start: 30 sec. on average

Dynamic Conditions

- Altitude of reception: Max. 18,000 Meter (60,000 Feet)
- Speed of reception: Max. 515 Meter /Second (1000 Knots)
- Acceleration: Max. 4g
- Vibration: Max. 20 m/s × 3

Power Supply

- Electrical connection: 5V DC
- Current draw: Approx. 80 mA

Interface Properties

- **USB 1.1**
- Baud rate: Auto
- Output protocol: NMEA 0183 GGA, GSA, GSV, RMC, VTG

NAVILOCK®

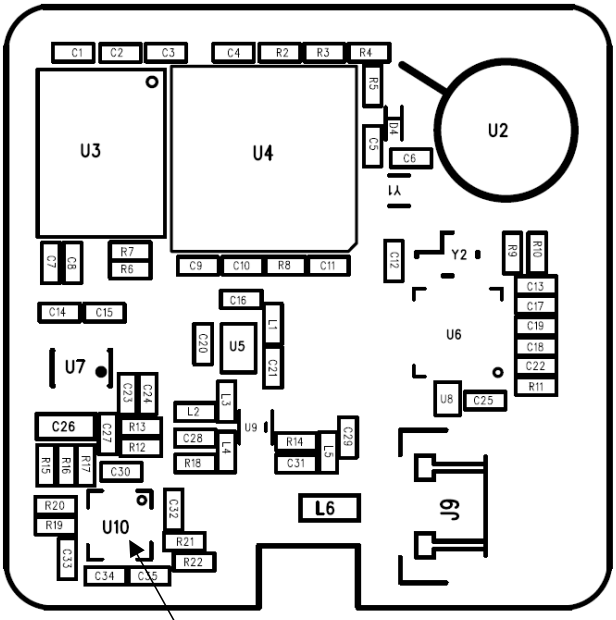
- **Serial RS232 Level**
- Baud rate: 38,400 bps
- Output protocol: NMEA 0183 GGA, GSA, GSV, RMC, VTG

TTL Level 3.3 Volt

- Baud rate: 38,400 bps
- 0 to 0.6 Volt TTL Low Level
- 2.31 to 3.3 Volt TTL High Level
- 3.3 Volt +/- 2% TTL Level Tolerance
- Output protocol: NMEA 0183 GGA, GSA, GSV, RMC, VTG

Physical Properties

- Dimensions: 30 mm x 30 mm x 7.9 mm
- Cable length: none (optional connection cable 95843 required (10 cm at open cable ends))
- Operating temperature range: -40℃ to +85℃



The USB/Serial Bridge "U10" is only populated on NL-550ERS.

Please refer to the ublox5 reference manual for protocol description.

It is available for download under:
http://www.navilock.de/produkte/gruppen/13/Boards_und_Module/60418_NL-550ERS_ublox5.html?show=datafile&type=7.

The NL-551EUSB requires a ublox5 USB driver which is available for download under:
http://www.navilock.de/produkte/gruppen/13/Boards_und_Module/60419_NL-551EUSB_ublox5.html?show=datafile&type=3.

D

DATASHEET MICROCONTROLLER

On the next three pages, the most relevant pages of the datasheet of the used microcontroller board [23] are included.

INTRODUCTION

LPC-P1343 is a development board with LPC1343 ARM Cortex-M3 based microcontroller for embedded applications from NXP. LPC-P1343 featuring a high level of integration and low power consumption. This microcontroller supports various interfaces such as one Fast-mode Plus I^2C-bus interface, USB, UART, SSP interfaces, four general purpose timers, a 10-bit ADC. On the board are available UEXT, Debug Interface, user buttons, USB device and user LEDs. This allows you to build a diversity of powerful software that can be used in a wide range of applications.

BOARD FEATURES

- MCU: **LPC1343** Cortex-M3, up to 70 MHz, 32 kB Flash, 8kB SRAM, UART RS-485, USB, SSP, I^2C/Fast+, ADC
- Power supply circuit
- Power-on led
- USB connector and functionality
- USBC LED
- Debug interface – SWD (Serial Wire Debug)
- UEXT connector
- Eight user LEDs
- Two user buttons
- Reset button
- Prototype area
- FR-4, 1.5 mm, red soldermask, white component print
- Dimensions:80x50mm (3.15 x 1.97")

ELECTROSTATIC WARNING

The **LPC-P1343** board is shipped in protective anti-static packaging. The board must not be subject to high electrostatic potentials. General practice for working with static sensitive devices should be applied when working with this board.

BOARD USE REQUIREMENTS

Cables: The cable you will need depends on the programmer/debugger you use. For instance, if you use https://www.olimex.com/Products/ARM/JTAG/ARM-JTAG-COOCOX/, you will need USB A-B cable.

Hardware: Programmer/debugger or other compatible programming/debugging tool with SWD interface. The only Olimex programmer that has SWD interface at the moment is ARM-JTAG-COOCOX – https://www.olimex.com/Products/ARM/JTAG/ARM-JTAG-COOCOX.

OpenOCD debuggers (ARM-JTAG-TINY, ARM-JTAG-TINY-H, ARM-JTAG-OCD, ARM-JTAG-OCD-H) can also be adapted to work with SWD interface by getting https://www.olimex.com/Products/ARM/JTAG/ARM-JTAG-SWD/. NOTE that at the current moment only Rowley Crossworks supports this combination.

PROCESSOR FEATURES

LPC-P1343 board use ARM Cortex™-M3 microcontroller **LPC1343FBD48/301** from NXP Semiconductors with these features:

- ARM Cortex-M3 processor, running at frequencies of up to 72 MHz
- ARM Cortex-M3 built-in Nested Vectored Interrupt Controller (NVIC).
- 32kB on-chip flash programming memory. Enhanced flash memory accelerator enables high- peed 72 MHz operation with zero wait states
- In-System Programming (ISP) and In-Application Programming (IAP) via on-chip bootloader software.
- Serial interfaces:
  - USB 2.0 full-speed device controller with on-chip PHY for device
  - UART with fractional baud rate generation, modem, internal FIFO and RS-485/EIA-485 support.
  - SSP controller with FIFO and multi-protocol capabilities.
  - I^2C-bus interface supporting full I^2C-bus specification and Fast-mode Plus with a data rate of 1 Mbit/s with multiple address recognition and monitor mode.
- Other peripherals:
  - 42 General Purpose I/O (GPIO) pins with configurable pull-up/down resistors and a new, configurable open-drain operating mode.
  - Four general purpose timers/counters, with a total of four capture inputs and 13 match outputs.

- Programmable WatchDog Timer (WDT).
- System tick timer.

– Serial Wire Debug and Serial Wire Trace Port.

– High-current output driver (20 mA) on one pin.

– High-current sink drivers (20 mA) on two I2C-bus pins in Fast-mode Plus.

– Integrated PMU (Power Management Unit) to minimize power consumption during Sleep, Deep-sleep, and Deep power-down modes.

– Three reduced power modes: Sleep, Deep-sleep, and Deep power-down.

– Single 3.3 V power supply (2.0 V to 3.6 V).

– 10-bit ADC with input multiplexing among 8 pins.

– 40 GPIO pins can be used as edge and level sensitive interrupt sources.

– Clock output function with divider that can reflect the main oscillator clock, IRC clock, CPU clock, Watchdog clock, and the USB clock.

– Processor wake-up from Deep-sleep mode via GPIO interrupts.

– Brownout detect with four separate thresholds for interrupt and one threshold for forced reset.

– Power-On Reset (POR).

– Crystal oscillator with an operating range of 1 MHz to 25 MHz.

– 12 MHz internal RC oscillator trimmed to 1 % accuracy that can optionally be used as a system clock.

– PLL allows CPU operation up to the maximum CPU rate without the need for a high-frequency crystal. May be run from the main oscillator, the internal RC oscillator, or the Watchdog oscillator.

– Code Read Protection (CRP) with different security levels.

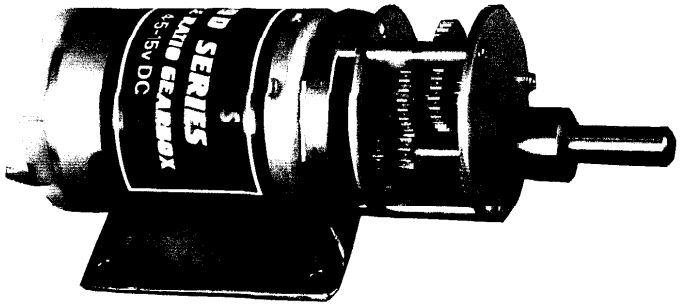
E

DATASHEET MOTOR

On the next two pages, the datasheet of the used motors [33] are included.

MFA / COMO DRILLS

919D SERIES SINGLE RATIO METAL GEARBOX (RE 540/1 MOTOR)



RATIOS NOW AVAILABLE AS EX-STOCK ITEMS.

NEW!	919D2.51	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 2.5:1
	919D61	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 6:1
	919D111	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 11:1
	919D501	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 50:1
	919D1481	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 148:1
	919D8101	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 810:1
NEW!	919D30001	(4.5v - 15v)	WITH RE 540/1 MOTOR.	RATIO 3000:1

Designed for heavy-duty industrial and model applications this robust unit boasts a powerful high quality, three pole motor with sintered bronze bearings. The all steel gearbox incorporates bronze output bearings, enabling the high torque transfer from the motor to be transmitted through the gearbox. The unit is mounted on a 1mm thick plated steel bracket.

MOTOR DATA. (RE-540/1)

MODEL	VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY						STALL TORQUE	
	OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	EFF		
			R.P.M.	A	R.P.M.	A	oz - in	g - cm	W	%	oz - in	g - cm
RE - 540/1	4.5 - 15.0	6.0v CONSTANT	7500	0.45	6180	2.1	1.64	118.2	7.49	59.4	9.31	670
		12.0v CONSTANT	15800	0.52	13360	2.85	2.14	154.4	21.2	61.9	13.9	1000

REDUCTION TABLE. R.P.M.

SUPPLY VOLTAGE	4.5v	6.0v	9.0v	12.0v	15.0v
919D2.51	2250	3000	4500	6300	7900
919D61	990	1316	1975	2633	3295
919D111	*540*	*718*	*1077*	*1436*	*1800*
919D501	120	158	237	316	395
919D1481	40	53	80	106	132
919D8101	8	10	15	20	25
919D30001	1.5	2	3	5	6

WEIGHT	
919D2.51	240g
919D61	234g
919D111	*238g*
919D501	246g
919D1481	255g
919D8101	255g
919D30001	262g

TORQUE TABLE (g.cm). (Theoretical rating for motor & gearbox combined).

	AT MAXIMUM EFFICIENCY 6V	AT MAXIMUM EFFICIENCY 12V	STALL TORQUE 6V	STALL TORQUE 12V
RE 540/1 (2.5)	295	386	1675	2500
RE 540/1 (6:1)	709	926	4020	6000
RE 540/1 (11:1)	1300	1698	7370	11000
RE 540/1 (50:1)	5910	7720	33500	50000
RE 540/1 (148:1)	17493	22851	99160	148000
RE 540/1 (810:1)	95742	125064	542700	810000
RE540/1(3000:1)	354600	463200	2010000	3000000

IMPORTANT NOTICE
Due to the wide range of applications for this product it is the users responsibility to establish the products suitability for their individual purpose(s).

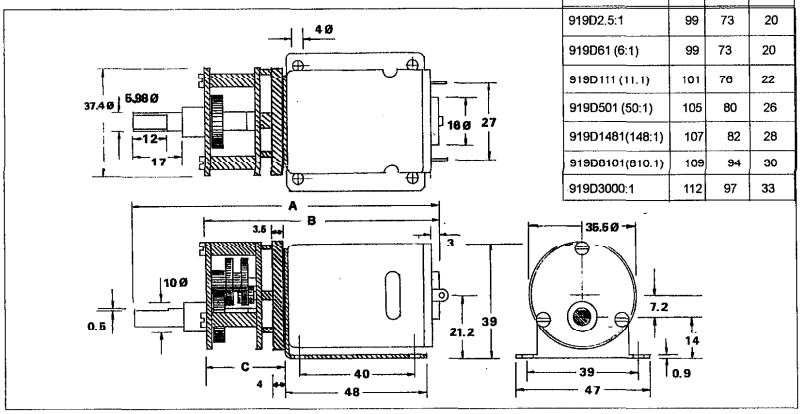
NOTE: To establish Torque Rating in nM divide g.cm by 10,197.0

THE ABOVE FIGURES ARE A GUIDE ONLY AND DO NOT FORM ANY CONTRACTUAL OBLIGATION ON THE PART OF MFA/COMO DRILLS

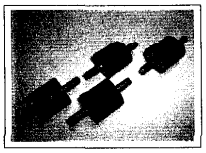
MFA / COMO DRILLS

919D SERIES SINGLE RATIO METAL GEARBOX (RE 540/1 MOTOR)

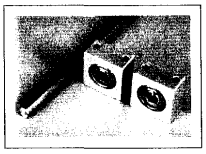
GEARBOX DIMENSIONS



GEARBOX REF.	A	B	C
919D2.5:1	99	73	20
919D61 (6:1)	99	73	20
919D111 (11.1)	101	76	22
919D501 (50:1)	105	80	26
919D1481(148:1)	107	82	28
919D6101(610.1)	109	84	30
919D3000:1	112	97	33

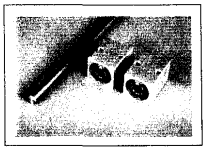


Part No. 1071. Anti vibration mount. M3



Part No. 919D30
Bearing Blocks. 5mm I.D.

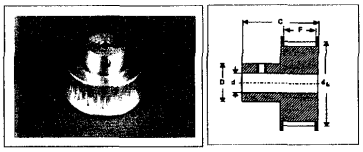
Part No. 919D26
Steel shaft 5mmOD x 150mm



Part No. 919D30/1
Bearing Blocks. 6mm I.D.

Part No. 919D26/1
Steel Shaft 6mmOD x 150mm

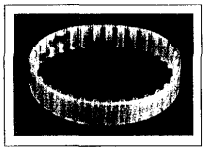
TIMING PULLEYS



Part No. 919D7 - 14. Timing Pulleys.

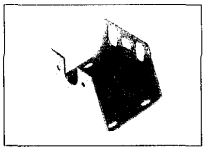
Pt. No.	No. of teeth	d	dk	F	C	D
919D7	14	6	21.45	12	21.0	12
919D8	16	6	24.60	12	21.0	15
919D9	20	6	31.00	12	21.0	15
919D10	25	6	39.00	12	21.0	15
919D11	30	6	46.95	12	21.0	15
919D12	35	6	54.85	12	21.0	15
919D13	40	6	62.85	12	21.0	15
919D14	44	6	69.20	12	21.0	15

TIMING BELTS

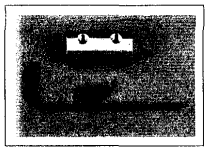


Part No. 919D15 - 23. Timing Belts.

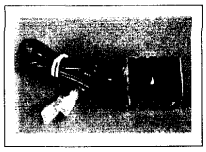
Pt. No.	Length	Width
919D15	165	9.8
919D16	185	9.8
919D17	200	9.8
919D18	305	9.8
919D19	390	9.8
919D20	455	9.8
919D21	545	9.8
919D22	630	9.8
919D23	840	9.8



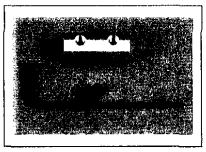
Part No. 919D29
Double ended motor mount.



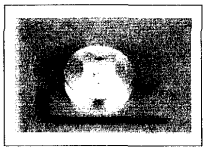
Pt No. 919D1. In-Line Coupling. 6mm - 6mm.(Dia. 12.67mm x 24.8mm)



Pt No. 919D2. Voltage Regulator.(6-15v DC Input. 4v-12v output). 26mm x 31mm x 15.5mm

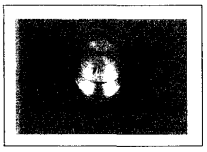


Pt No. 919D3. In-line Coupling. 6mm-8swg (Meccano) Dia. 12.67mm x 24.8mm

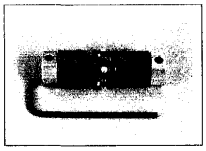


Pt No. 919D4. Pulley 25mm dia. (Aluminium)

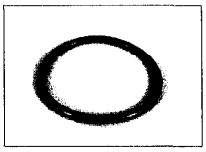
Pt.No.919D24. Bevel Gearbox. (Right Angle)



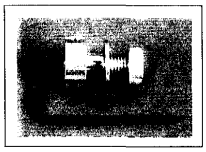
Pt No. 919D5. Pulley 16mm dia.(Aluminium)



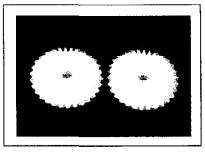
Pt No. 919D6. Universal Coupling. 6mm - 6mm.



Pt No. 917D2515. "O" Ring 70mm x 5mm Dia.



Pt No. 919D27. Gear Adapter.



Pt No. 919D25. Nylon Bevel Gears 1:1. OD30.7mm ID 6mm

Subject to minimum order quantities of 250 units, the following ratios are also available with a six week lead-time. The physical dimensions of these other gearboxes may vary from the data as illustrated above. Details of individual gearboxes are available upon request.

GEARBOX 18:1 WITH 540/1 MOTOR.
GEARBOX 70:1 WITH 540/1 MOTOR.
GEARBOX 100:1 WITH 540/1 MOTOR
GEARBOX 200:1 WITH 540/1 MOTOR
GEARBOX 350:1 WITH 540/1 MOTOR
GEARBOX 500:1 WITH 540/1 MOTOR
GEARBOX 900:1 WITH 540/1 MOTOR

GEARBOX 30:1 WITH 540/1 MOTOR.
GEARBOX 75:1 WITH 540/1 MOTOR.
GEARBOX 120:1 WITH 540/1 MOTOR
GEARBOX 250:1 WITH 540/1 MOTOR
GEARBOX 400:1 WITH 540/1 MOTOR
GEARBOX 600:1 WITH 540/1 MOTOR
GEARBOX 1000:1 WITH 540/1 MOTOR

GEARBOX 60:1 WITH 540/1 MOTOR
GEARBOX 90:1 WITH 540/1 MOTOR.
GEARBOX 180:1 WITH 540/1 MOTOR
GEARBOX 300:1 WITH 540/1 MOTOR
GEARBOX 450:1 WITH 540/1 MOTOR
GEARBOX 700:1 WITH 540/1 MOTOR
GEARBOX 1500:1 WITH 540/1 MOTOR

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